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PREDICTING AURAL DETECTABILITY OF AIRCRAFT IN NOISE BACKGROUNDS

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PREDICTING AURAL DETECTABILITY OF AIRCRAFT IN NOISE BACKGROUNDS

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FOREWORD

This report was prepared by Bolt Beranek and Newman, Inc., for the Aero-Acoustics Branch, Vehicle Dynamics Division, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, under Contract F33615-71-C-1220. The work described herein is a part of the Air Force Systems Command exploratory development program to predict the noise environment of flight vehicles. The work was directed under Project 1471, "Aero-Acoustics Problems in Air Force Flight Vehicles," Task 1471 02, "Prediction and Control of Noise Associated with USAF Flight Vehicles". Capt. R. P. Paxson of the Aero-Acoustics Branch was the task engineer.

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This Technical Report has been reviewed and is approved.

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ABSTRACT

Laboratory experiments were undertaken to develop improved aural detection criteria for light aircraft. Specifically two series of psychoacoustic judgment tests were conducted to determine the applicability of the psychophysical Theory of Signal Detectability (TSD) to prediction of the aural detectability of light aircraft noise signatures in jungle noise backgrounds. The first series of tests produced data supporting development of a simplified graphical prediction method based on TSD. The second testing program validated the precision and accuracy of the prediction method under quasi-realistic listening conditions. Predicted levels of performance were typically within one or two dB of the data averaged for all observers.

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SECTION I.
INTRODUCTION

Recently there has been some interest in designing quiet light aircraft. For such designs it is necessary to know the noise levels of aircraft which are detectable. Although some investigations have been carried out to develop methods for determining detection levels, some improvement is required. Therefore a development program was undertaken to improve aural detection criteria for light aircraft

Aural detection of light aircraft noise by human observers under field conditions is a complex task. It depends not only upon the physical characteristics of the aircraft noise signature and the ambient noise of the listening environment, but also upon the sensitivity of the observer, his state of attention, a priori information available to the observer, and the costs and payoffs associated with the outcomes of the observer's detection decisions. The research program described in the current report was undertaken to develop a relatively straightforward method of predicting human performance in the aural detection task so that reliable information on the probability of detection of current and future aircraft would be available to both design and tactical personnel.

The theoretical approach adopted to simplify and quantify the various factors influencing detection performance is the psychophysical Theory of Signal Detectability. Application of this theory to the aural detection task in the field is described at length in Section II. Section III presents the methods and results of three experiments conducted to validate the prediction method. Section IV is a detailed discussion of the proposed aural detection criteria. Section V summarizes the main conclusions of the study. A number of appendices containing finer detail on procedures, data, and measurements accompany the main body of the report.

SECTION II

PSYCHOPHYSICAL THEORY OF SIGNAL DETECTABILITY

As mentioned briefly in the introduction, prediction of human performance in the aural detection task demands understanding of both physical and psychological factors. The psychophysical Theory of Signal Detectability (TSD) (Reference 1) provides a theoretical framework for joint consideration of these factors. The underlying assumption of the current application of TSD is that human detection performance may be likened to an ideal energy detection process. Thus, the basic physical quantity upon which human detection performance rests is the signal to noise ratio. For purposes of simplicity, this quantity is measured in independent one-third octave bands according to procedures discussed in greater detail in the following section.

In theory, an energy detector could make detection decisions in the following fashion. First, any sample of acoustic energy would be assumed to derive from one of two distributions. The distributions are those of noise alone, and signal plus noise. For computational convenience the two distributions are assumed to be normal in nature and of equal variance. In practical terms, the distance between the means of the two distributions is given by the measured signal to noise ratio. As the signal to noise ratio increases, the decision task becomes simpler. A standardized statistic known as d' (d prime) may be calculated to determine the sensitivity of an energy detector working on any given set of distributions. The d' statistic, defined as the distance between the means of the two distributions divided by the standard deviation of the noise distribution, is monotonic with the signal to noise ratio and directly proportional to the quantity $2E/N_0$ (twice the signal energy divided by the noise power per unit bandwidth).

Next, the probability that the sample of acoustic energy could have been generated by the noise process alone and by the sum of the signal plus noise processes is evaluated. An optimal manner of combining the information represented by these two probabilities is to form their ratio, referred to as a likelihood or odds ratio. It has been shown (Reference 1) that decisions based on likelihood ratios are optimal in the sense that all available physical information about the presence of the signal is incorporated in such a statistic. The numerator of the statistic commonly represents the probability that the observation belongs to the distribution of signal plus noise, while the denominator represents the probability that the same observation belongs to the distribution of noise alone.

It must be emphasized that even an ideal energy detector operating in this fashion is fallible. If, for example, the likelihood ratio is 1 (i.e., it is equally likely that the observation belongs to the noise alone or to the signal plus noise distribution), the decision must be based on grounds other than the physical observation. In fact, it should be apparent that a criterion is *always* necessary to make a decision. Although the criterion may be expressed in terms of a likelihood ratio (e.g., "report the presence of a signal whenever the likelihood ratio exceeds 10"), the criterion must be based upon non-physical factors. Foremost among these non-acoustic factors are the costs and payoffs associated with the decision outcomes.

The four outcomes of any detection decision are readily enumerated. A "hit" may be defined as a decision to report the presence of the signal when the signal is actually present. A "miss" may be defined as a decision not to report the presence of a signal when it is in fact present. A "false alarm" results from a decision to

report the presence of the signal in the absence of a signal, while a "correct rejection" represents a decision not to report the presence of the signal when it is in fact not present.

The values of the four decision outcomes are determined by the context of the situation in which the decision must be made. Certain situations may favor a high false alarm rate (i.e., a lax likelihood ratio criterion with a very low value), while other situations may favor a very high correct rejection rate (i.e., a stringent likelihood ratio with a very high value). Note that the fundamental sensitivity of the observer, as expressed in d' units, is entirely independent of the criterion employed in producing a decision. Thus, the same observer, of fixed sensitivity, is capable of producing widely divergent behaviors. In some situations, the observer may achieve an extremely high hit rate (albeit at the expense of a concomitantly high false alarm rate). In other situations, the observer may achieve a very low hit rate, with a concomitant reduction in the false alarm rate.

The plot of hit rates versus false alarm rates for an individual observer of fixed sensitivity is referred to as a "Receiver Operating Characteristic". Figure 1 is a schematic representation of a family of ROC curves which is parametric in d'. The negatively accelerated, positively sloping function depicted by the ROC curve is a direct consequence of the assumptions of the common TSD model.

The remaining non-acoustic information which an ideal observer must consider in making a rational decision is the *a priori* probability of occurrence of a signal. In other words, the ideal observer has some indication (from whatever sources may be available) of the probability that any given observation interval will include a signal. In terms of the problem at hand, an

observer in a realistic detection task certainly has some expectations about the frequency of occurrence of overflights, even before he begins the listening task.

This information is most concisely expressed as an odds ratio, composed in a manner similar to a likelihood ratio. The numerator is usually the probability that a signal is present during an observation interval, while the denominator is the probability that the noise alone is present during the observation interval.

It has been shown that Bayes' Theorem (Reference 2) provides an optimal way to combine the *a priori* information with the likelihood ratio resulting from a particular observation. Bayes' Theorem is applied to the current situation by observing that the *a posteriori* odds in favor of the occurrence of a signal during a particular observation interval are equal to the simple product of the *a priori* odds (the odds in favor of occurrence of a signal in the interval, known before the observation is made) and the likelihood ratio (the odds in favor of occurrence of a signal based on the information contained in the observation).

The reader is referred to Reference 1 for more detailed discussions and mathematical proofs of the theoretical concepts presented above.

SECTION III
PSYCHOACOUSTIC JUDGMENT TESTS

1. Description of Tests IA and IB

Psychoacoustic experiments (referred to as Tests IA and IB below) were conducted to determine the applicability of TSD to prediction of the audibility of light aircraft noise signatures embedded in jungle noise backgrounds. The intent of Test IA was to establish the detectabilities of a number of different components of light aircraft noise signatures. The intent of Test IB was to determine the manner in which the detectabilities of the individual components combine to influence overall detectability.

a) Method for Test IA

Twelve synthetic signals were selected as representative of portions of the noise signatures of light aircraft. The twelve signals fell into three categories of spectral characteristics, including narrow band noises, broadband noises, and pure tones in low and medium frequency ranges. Two rates of frequency modulation and two amounts of amplitude modulation were applied to several of the signals as well. Observers heard the signals in each of three background noise environments. The background noises were similar to those of the day and night ambient noise in the jungle and to the more familiar noise background of modern inhabited areas. Table I catalogs the twelve signals and three background noises. Appendix I contains one-third octave band analyses of the signal spectra. Figure 2 plots the spectra of the background noises.

Ten observers between the ages of 16 and 24 years were employed in Test IA. Observers were audiometrically screened according to ISO Recommendation R-389. Observers were required to depress a response switch corresponding to the observation interval in which

TABLE I

ST[illegible]S FOR DETECTION TEST IA

	Tone or Noise	Bandwidth	Center Frequency	Modulation	Rate	Range	Comments
1	Tone	---	1-2 kHz	FM	2 Hz	1-2 kHz	Modulation wave form is triangular
2	Tone	---	1-2 kHz	FM	1 Hz	1-2 kHz	Modulation wave form is triangular
3	Noise	1/3 oct	500 Hz	AM	.5-2 Hz	13 dB	Frequency of AM modulator varies randomly from .5-2 Hz with fixed amplitude
4	Noise	1/3 oct	2000 Hz	AM	.5-2 Hz	13 dB	Frequency of AM modulator varies randomly from .5-2 Hz with fixed amplitude
5	Noise	1/3 oct	500 Hz	AM	.5-2 Hz	6 dB	Frequency of AM modulator varies randomly from .5-2 Hz with fixed amplitude
6	Noise	1/3 oct	2000 Hz	AM	.5-2 Hz	6 dB	Frequency of AM modulator varies randomly from .5-2 Hz with fixed amplitude
7	Noise	1/3 oct	500 Hz	--	--	---	
8	Noise	1/3 oct	2000 Hz	--	--	---	
9	Tone	---	250 Hz	--	--	---	
10	Tone	---	2000 Hz	--	--	---	
11	Noise	Broadband	---	--	--	---	Simulated "Sailplane"
12	Noise	Broadband	---	--	--	---	Simulated light powered aircraft
Bkgrd.							
1	Noise	Broadband	---	--	--	---	Shaped broadband noise with spectra equivalent to daytime jungle noise.
2	Noise	Broadband	---	--	--	---	Shaped broadband noise with spectra equivalent to nighttime jungle noise.
3	Noise	Broadband	---	--	--	---	Shaped broadband noise with spectra equivalent to suburban noise.

they thought they heard a signal in a two alternative forced choice task. Administration of experimental conditions was under the control of an automated psychophysical laboratory.

b) Method for Test IB

Fourteen signals were presented to observers for subjective judgment under conditions similar to those of Test IA. The fourteen signals included seven previously employed in Test IA, three signals constructed of quadruple combinations of the above seven signals, and four recorded aircraft flyovers. Table II summarizes the nature of the signals employed in Test IB. Ten observers, of whom eight had participated in Test IA, served in Test IB.

c) Experimental Design for Tests IA and IB

The trial procedure employed in Tests IA and IB was a computer-based adaptive technique known as Parameter Estimation by Sequential Testing (PEST), described in detail elsewhere (Reference 3). On a given trial an observer was required to depress one of two response switches to indicate to the computer his decision about which observation interval contained the signal. Observation intervals were four seconds long and separated by a one second intratrial period. Feedback was immediately presented in the form of a lighted response switch to indicate the interval in which the signal actually had occurred.

Fourteen hours per observer were required to complete the thirty-six (twelve signals by three background noises) listening conditions of Test IA. Seven experimental sessions per observer were scheduled at two hours each. Approximately eight hours, divided into four two hour sittings, were required for each observer to complete the fourteen listening conditions of Test IB.

TABLE II

SIGNALS FOR DETECTION TEST IB

	Tone or Noise	Bandwidth	Center Frequency	Modulation	Rate	Range	Comments
1	Tone	---	1-2 kHz	FM	2 Hz	1-2 kHz	Modulation wave form is triangular
2	Noise	1/3 oct	500 Hz	AM	.5-2 Hz	13 dB	Frequency of AM modulator varies randomly from .5-2 Hz with fixed amplitude
3	Noise	1/3 oct	2000 Hz	AM	.5-2 Hz	6 dB	
4	Noise	1/3 oct	500 Hz	--	--	---	
5	Tone	---	2000 Hz	--	--	---	
6	Noise	Broadband	---	--	--	---	Simulated sailplane
7	Noise	Broadband	---	--	--	---	Simulated light powered aircraft
8	Signals	Combinations of:	3, 4, 5, 7				
9	Signals	Combinations of:	1, 2, 3, 5				
10	Signals	Combinations of:	2, 3, 4, 6				
11	Aircraft	---	---	--	--	---	Libelle
12	Aircraft	---	---	--	--	---	Schweizer 2-32
13	Aircraft	---	---	--	--	---	Beechcraft
14	Aircraft	---	---	--	--	---	Aren
Bkgrd. 1	Noise	Broadband	---	--	--	---	Shaped broadband noise with spectra equivalent to daytime jungle noise.

Each observer completed five repeated determinations of the 75% correct detection point in succession in Test IA. A brief break was provided between sets of determinations; a five minute break was provided after each half hour in the anechoic chamber. All observers encountered the various listening conditions in both tests in different random orders. Appendix III contains further detail on observers and equipment employed in these tests.

2. Results of Tests IA and IB

The principal findings of Test IA are presented graphically in Figures 3 and 4. Data in these figures are plotted in the form of deviations from a predicted level of performance. The prediction scheme employed in Test IA was a statistical summation of the detectabilities of signals calculated from signal to noise ratios in third octave bands. The prediction method is described in detail in Appendix IV. The data of Figure 3 are the averages of all observers' five determinations of the 75% detection level for each signal in each noise background. The zero line of Figure 3 represents the predicted level of performance. The vertical distances of data points from the zero line are therefore directly interpretable as deviations from prediction. Figure 4 provides an indication of the variability associated with the deviations from predicted performance for each of the twelve signals, collapsed over the three noise backgrounds.

It must be realized that Figures 3 and 4 express only deviations from predicted levels, not absolute levels. Since there is a 37 dB(A) *range* of predicted levels among the twelve signals and three noise backgrounds, and since the average deviation from prediction is only 2.8 dB, a plot of absolute levels would show an excellent fit of the data to the prediction.

The goodness of fit of the predicted d's to the data of Test IA confirmed the applicability of the TSD to aural detection of light aircraft noise in various noise backgrounds. No special problems were encountered in predicting the detectabilities of "peculiar" signals; i.e., those containing amplitude or frequency modulation.

In order to produce the best fit of the predicted to the observed detectabilities it was necessary to assume that the observers' efficiency was 0.4 with respect to an ideal energy detector. This value is consistent with previously reported findings (Reference 4), particularly in light of the well defined observation intervals and immediate feedback available to observers.

Figure 5 presents the principal findings of Test IB in graphical form. Since the intent of Test IB was to determine the manner in which the detectabilities of discrete components of aircraft noise are combined by observers to yield overall detectability, two different prediction schemes were entertained. The upper plot of Figure 5 demonstrates the fit of the data to the predictions made by the statistical summation rule discussed in Appendix IV. The lower plot of Figure 5 demonstrates the fit of the data to predictions made by a d'_{max} rule discussed in Section IV. The average deviation of the data from the predicted values for the statistical summation predictions was -1.66 dB, while the average deviation from the predicted values for the d'_{max} rule was -0.33 dB. One statistical procedure for evaluating the significance of the difference between means of different samples is the t test. The value of the t statistic (with 13 degrees of freedom) for the difference between the average deviations from predicted values for the d'_{max} and statistical summation rules was 4.2. The likelihood of obtaining a value of the t statistic this large or larger by chance alone is less than 0.01. Thus, it was concluded that the d'_{max} rule provided significantly better predictions than the statistical summation rule.

The inclusion of seven signals of Test IA in Test IB presented an opportunity to assess the test-retest reliability of experimental conditions over a period of months. The average differences in the observers' detection performance for the seven signals included in the two tests was 0.8 dB. This difference of less than 1 dB was interpreted as confirmation of the stability of test conditions and the generality of predictions based on signal detection theory.

The greater accuracy of prediction afforded by the d'_{max} rule was not expected. It appears that the observers in Test IB "locked on" to the most detectable component of the complex signals (the three quadruple combinations and the four flyovers) and ignored information present in other spectral regions. Greater familiarity with the signals gained through extensive experience might encourage observers to modify their detection strategy to listen for more than one component of complex signals.

Figure 6 summarizes on one plot the effectiveness of the d'_{max} rule. All of the signals of Tests IA and IB are plotted in this figure on the same basis as in previous figures in this section. Twelve points fall above the predicted line, twelve points fall below the line, and two fall exactly on the line. The accuracy of the prediction is thus confirmed. The precision of the prediction is indicated by very small deviations of the predicted from the observed values.

3. Description of Test II

The design of Test II was intended to permit assessment of how well the prediction procedures developed in Tests IA and IB worked in quasi-realistic listening conditions. Accordingly, Test II was administered as a vigilance task, in which observers were ignorant

of the time of presentation of a signal. Continuous jungle noise* (Figure 7) was heard at all times, while no other cues were provided as to the time of occurrence of a signal.

The observer's task was to depress a response button whenever he decided that a signal was in fact being presented. A response made while the signal was presented, or within a half second grace period following the conclusion of the signal, counted as a correct detection (hit). A response made in the absence of a signal was counted as a false alarm. Failure to respond during the presentation of a signal or the grace period was registered as a miss. The instructions to observers are included in Appendix II.

Signal levels corresponding to 25%, 50%, and 75% correct detection performance were estimated using the PEST procedures. Hits and misses were employed to determine the required level changes. False alarms were tabulated to permit estimation of false alarm rates but had no direct bearing on the progress of a PEST run. A payoff schedule which penalized observers five cents for each false alarm, to be subtracted from a fixed bonus of $1.00 for each experimental session, was introduced to control the false alarm rate. Three PEST runs were administered to determine each of the three performance levels of the psychometric function.

The duration of intertrial intervals (the waits between successive presentations of signals) were determined according to an exponential distribution of waiting times. The exponential distribution was selected so that observers would have no information about the time of occurrence of the next signal. Thus, it was equally likely that a next signal would be heard immediately or after the longest delay.

* The recording of Panamanian jungle noise was made available through the courtesy of Mr. Richard Wells of General Electric Company, Schenectedy, New York.

Two different exponential distributions were employed. Data were collected for all signals with a distribution of waiting times that ranged from four seconds (the minimal wait occasioned by the duration of the signal tapes themselves) to approximately one hundred seconds. Data for signal six were also collected with a distribution of waiting times four times as long. The longest wait between signals in the longer distribution was approximately five and a half minutes (385 seconds). The purpose of collecting data under the longer waiting time distribution was to permit assessment of the extrapolation of detection performance to even greater waiting times.

The order of administration of experimental conditions (i.e., different levels of correct detection performance) was randomized, as was the order of testing of signals. Observers were carefully cautioned in their instructions to avoid the "gambler's fallacy" of expecting a signal to occur imminently simply because it has not occurred for a subjectively long period of time.

Except for the changes in trial procedures noted above, the equipment and physical conditions of testing were similar to those of Tests IA and IB. Further detail of the observers and equipment employed in Test II may be found in Appendix III.

The signals presented to observers in Test II included tones, noises, and aircraft flyovers from Tests IA and IB, as shown in Table III. Detailed one-third octave band analyses of the signals and background appear in Appendix I.

4. Results of Test II

The major findings of Test II are summarized in Figures 8 and 9. Figure 8 displays averaged data for all observers, showing the mean and standard deviations for all signals under investigation

TABLE III

SIGNALS FOR DETECTION TEST II

	Tone or Noise	Bandwidth	Center Frequency	Modulation	Rate	Range	Comments
1	Tone	---	1-2 kHz	FM	2 Hz	1-2 kHz	Modulation wave form is triangular
2	Signals	Combination	(same as stimulus 9 of Table II)				
3	Aircraft	---	---	--	--	---	Libelle
4	Aircraft	---	---	--	--	---	Schweizer 2-32
5	Aircraft	---	---	--	--	---	Beechcraft
6	Aircraft	---	---	--	--	---	Wren
7	Noise	1/3 oct	2000 Hz	AM	.5-2 Hz	13 dB	Frequency of AM Modulator varies randomly from .5-2 Hz with fixed amplitude
Bkgrd.							Recorded Jungle Noise

at the 50% correct response rate. The shaded area about the mean indicates one standard deviation above and below the mean. As may be seen, these standard deviations are quite small, on the order of 1 or 2 dB in most cases.

Predictions based on the method using d'_{max} specified in Section IV of this report (solid arrow) and upon the method developed by the Air Force Flight Dynamics Laboratory (AFFDL) and specified in References 5 and 6 (AFFDL method, dotted arrow) are also displayed in Figure 8. The method developed by BBN can be used to predict detection levels for various correct response rates and false alarm rates. The rates chosen as described in Section IV for the prediction method are 50% for correct response and 1% for false alarm. Predictions for all signals based on TSD by BBN are typically within 2 dB of the data. Predictions based on the AFFDL method differ generally in level from the predictions made by BBN, and in some cases are considerably divergent from the data. One difficulty encountered in using the AFFDL method was deciding whether or not a pure tone existed in the signal. For example, signals 3 and 4 were borderline cases so two predictions were made. The higher predicted levels in Figure 8 were the result of assuming no pure tone content while the lower levels resulted from a "pure-tone-present" assumption. The mean subjective response did lie between the two predictions but the differences in predictions encompassed a range of 13 dB, an amount greater than desirable.

As stated above, it appears that predictions based on the BBN method came closer to the data than those based on the AFFDL method. This is further illustrated by noting that BBN predictions for five of the seven signals were well within a standard deviation of the mean data while the AFFDL method produced predictions for only two to three of the seven signals which fell similarly close to the mean (depending on the tonal content assumptions).

The greatest differences between the two prediction methods were observed for the sixth and seventh signals. The BBN prediction for signal 6, an aircraft flyover with no tonal content, was about 1 dB from the mean, as opposed to 9 dB from the mean for the AFFDL prediction. For signal 7, the BBN prediction was about 0.5 dB from the mean, while the AFFDL method predicted a level 15 dB different from the mean. Thus, for those signals which do not contain pure tones, the AFFDL prediction method produces poor estimates of the 50% correct detection level and for those signals where the tonal content is in question, the range of predictions may be as high as 13 dB.

Figure 9 displays the BBN predictions and the observed results (averaged over observers again) for the 25%, 50%, and 75% correct detection levels. Since the AFFDL method produces no predictions for levels other than 50% correct detection, no effort was made to display such predictions in Figure 9. Once again, agreement between observed and predicted levels is quite good (within 2 dB for 75% of the cases) at all three detection rates. Agreement between the observed and predicted slopes is especially noteworthy, suggesting the feasibility of extrapolation to other detection rates than those measured.

Predicted values for the differences between the 25% and 50% correct detection levels, and the 50% and 75% correct detection levels were 1.6 and 1.1 dB, respectively. The corresponding differences actually observed were 1.2 dB and 0.9 dB, respectively. Although both the expected and observed values suggest the narrowness of the "detection aperture", it should be noted that the values increase with increases in the false alarm rate, as seen in Table IV of Section IV. The differences between 30% and 50% correct detection levels and 50% and 70% correct detection levels becomes 6.5 dB and 2.5 dB, respectively, for a 25% false alarm rate.

5. Discussion and Summary

Two series of subjective judgment tests were conducted to determine the applicability of the psychophysical Theory of Signal Detectability (TSD) to prediction of the levels at which light aircraft are aurally detectable in jungle noise backgrounds. Tests IA and IB demonstrated the applicability of TSD to the current problem, while providing data for the evolution of a simplified graphic prediction method. Test II provided verification of the prediction method under quasi-realistic listening conditions.

A number of grounds were found on the basis of the current research to prefer the TSD approach to prediction of aural detectability to other approaches, such as the AFFDL method specified in Reference 5. First, the TSD method provides a better fit, on the average, to the data. Second, it is more general, in that it permits prediction of performance at levels other than 50% correct detection and at specified false alarm rates. Third, it is simpler, since it requires no distinctions to be made on the basis of the tonal content of aircraft noise signatures. Fourth, the TSD approach is firmly based in theory, and thus capable of extension to novel situations, unforeseen detection strategies, and so forth.

SECTION IV
PROPOSED AURAL DETECTION CRITERIA

1. Development of Criteria

Section II of this report has outlined the nature of the sensitivity measure d' and its interactions with non-acoustic factors in determining human detection performance. In developing a straightforward prediction method, a number of assumptions were made to permit simplification of the method, and to make maximal use of acoustic information about the levels of aircraft and background noises. First, it was assumed that observers have diffuse a priori information about the presence of aircraft during the detection task. This assumption was made of necessity, since it is not possible to quantify this sort of information in a graphic prediction method. Second, it was necessary to assume a false alarm rate consistent both with hearing threshold data which appear in the graphical method and with the nature of the detection task in the field. Justification for these assumptions will be found in later discussions.

The essence of the proposed method for predicting the detectability of light aircraft noise in jungle noise backgrounds is that human performance is based on the signal to noise ratio in the single one-third octave band to which human sensitivity is highest. The basic data employed in the proposed method are therefore the one-third octave band spectra of the aircraft noise and of the jungle noise.

These data are used to determine the value of the sensitivity measure d', as discussed in the previous section. The equation which estimates d' is as follows:

$$d' = \frac{\eta\ S(W)^{\frac{1}{2}}}{N} \qquad (1)$$

where η is an expression of the efficiency of a human observer with respect to an ideal energy detector, S is the signal level in a one-third octave band, N is the background noise level in the same one-third octave band, and W is the one-third octave bandwidth.

Equation 1 may be solved for the signal to noise ratio for specific cases of interest. For example, experimental data collected in Tests IA and IB (see Section III) yield a value of 0.4 for η. For reasons discussed below, a 50% correct detection rate and a 1% false alarm rate were selected as values of especial interest for present purposes. These values yield a d' of 2.32 (Reference 7), so that

$$10 \log (S/N) = 10 \log \frac{2.32}{0.4(W)^{\frac{1}{2}}} \qquad (2)$$

Thus, for example, a signal in the one-third octave band centered at 1000 Hz would be detected 50% of the time, with a false alarm rate of 1%, when the signal is 4.2 dB below the level of the noise in the same one-third octave band.

2. Procedures for Evaluating Aural Detectability of Aircraft

A special graph has been prepared (Figure 10) to facilitate determination of the level at which aircraft will be detectable with specified probabilities. This figure embodies the assumptions noted above and the conditions of Equation 2 in order to reduce the mechanical aspects of the prediction scheme to a minimum. The plot of the threshold of pure tones (Reference 8) in Figure 10 may be interpreted as the level at which an average human observer is capable of detecting a signal 50% of the time in the absence of external background noise. No plotting should be done below this curve. Figure 10 also includes a special set of ordinates (indicated by the sloping grid lines) for use in plotting the

background noise spectrum in one-third octave bands. When the background noise is plotted on the special grid of Figure 10, it may be used (in conjunction with the pure tone threshold) to produce the predicted one-third octave band detection levels. These intermediate detection levels are then to be used directly with a plot of the signal spectrum in one-third octave bands for generating the final prediction.

Knowing the detection level for a given background noise and the one-third octave band sound levels of the aircraft at a given altitude, the one-third octave band which exhibits the greatest difference can be determined. This difference is the amount that the aircraft noise must be reduced to meet the 50% detectability requirements. The change in altitude necessary to meet the requirements may be determined by the method outlined in Reference 6. A condensed summary of the entire evaluation procedure is given in Appendix V.

Figure 10 may also be employed to produce predictions of detection performance at other false alarm rates and other percentages of correct detection. Such predictions are derived by adjusting the 50% correct detection rate via the correction terms contained in Tables IV and V. Some understanding of the assumptions implicit in Figure 10 may be helpful in making such adjustments.

The false alarm rate upon which Figure 10 is based is 1%. This rate was selected to provide agreement with test results discussed in Section III and field judgment test results gathered by AFFDL (Reference 5). The 1% false alarm rate implies that the observer is extremely cautious, only reporting signals when he has considerable confidence. However, someone selected to listen for hostile aircraft might be encouraged to adopt a fairly lax criterion for reporting their presence, since a strict criterion

TABLE IV

ADJUSTMENT OF 50% DETECTABILITY LEVEL
FOR VARIOUS FALSE ALARM RATES

False Alarm Rate	d'	Adjustment Added to 50% Detectability Level
1%	2.32	0 dB
5%	1.64	-1.5 dB
10%	1.28	-2.5 dB
15%	1.04	-3.5 dB
20%	.84	-4.5 dB
25%	.68	-5.5 dB
30%	.52	-6.5 dB
35%	.38	-8.0 dB
40%	.26	-9.5 dB
45%	.13	-12.5 dB

TABLE V

ADJUSTMENT OF 50% DETECTABILITY LEVEL TO OTHER PERCENT CORRECT WITH 1% FALSE ALARM RATE

Correct Detection Rate	d'	Correction to be Added to 50% Detectability Level
10%	1.04	-3.5
20%	1.48	-2.0
30%	1.80	-1.0
40%	2.06	-0.5
50%	2.32	0
60%	2.58	+0.5
70%	2.84	+1.0
80%	3.16	+1.5
90%	3.60	+2.0

could lead to an intolerably high miss rate. In that case a false alarm rate of 25% might be appropriate. In the long run, an observer with a flase alarm rate of 25% would be correct three times out of four when he reported the presence of a signal.

3. Comparison of Predicted and Subjective Determination of the Aural Detectability of the Schweizer 2-33.

Some judgment tests with four observers were conducted in a field situation by AFFDL (Reference 5) to determine the altitude the Schweizer 2-33 should fly to be "just detectable". The results of the test indicated an altitude of 2200 to 2400 feet. All observers claimed to hear the plane at 2200 feet altitude (Reference 5). Personal communication with AFFDL revealed that one observer also claimed to hear the aircraft at 2400 feet. The altitude may be estimated by using data supplied in Reference 5 and the prediction method outlined in this report. Actually, the example in Appendix V utilizes these data resulting in a predicted altitude of 2200 feet. This figure is in close agreement with the *subjective* test results. Results were also obtained with the AFFDL method which predicted an altitude of 1300 feet. The lack of agreement between two prediction methods for this particular case is attributed to the absence of tonal components in the aircraft noise.

4. Other Factors Affecting the Aural Detectability of Aircraft

Assumptions about the probability of occurrence of aircraft over-flights in the field depend upon tactical information, entirely unrelated to acoustic considerations. Since such considerations are beyond the scope of this report, no attempt was made to incorporate assumptions of this sort into the prediction method. It is noted in passing, however, that strong a priori information about the presence or absence of aircraft could play a large role in determining detection rates. Further, a correct detection does not imply recognition or identification. Recognition may require higher levels than those associated with detection.

Knowledge gained from the conduct of the two test series permits a number of observations about the possibility of facilitating aural detection by semi-sophisticated listening aids. First, to the extent that human detection performance is determined by signal to noise ratios in the low frequency (below 250 Hz) portion of aircraft noise spectra, it may be possible to enhance detectability by simple amplification in this frequency region. Such increments in signal to noise ratios are practical because of the peculiar nature of jungle noise, which contains relatively little energy at low frequencies.

Thus, a crude horn of dimensions favoring low frequency transmission might function as a primitive listening aid. Electronic amplification of the low frequency portion of the spectrum could be even more effective. Substantial gain would be needed to render audible the portion of the aircraft noise signature which enjoys the least masking from jungle noise.

Second, enhancement of detection performance may also be achieved in another way. It has been demonstrated (Reference 4) that multiple observers making independent decisions are capable of better performance than single observers. Thus, two or three well trained observers working independently (perhaps with the help of some listening device) might well be capable of higher hit rates than a single observer. The improvement in sensitivity (and hence, detection performance) so achieved could be on the order of 3 to 10 dB.

SECTION V
CONCLUSIONS

Six major conculsions may be drawn from the present research.

1. The psychophysical Theory of Signal Detectability provides reasonable predictions (within 1 or 2 dB of the data) of detectability levels for light aircraft noise signatures embedded in various background noises.

2. Human aural detection of aircraft seems to be based on the signal to noise ratio in the single one-third octave band to which human sensitivity is highest.

3. Agreement between predictions based on TSD and those based of the AFFDL method (Reference 3) is best (within 3 dB generally) for signals with definite tonal content. For signals lacking pure tones the AFFDL method is difficult to apply and differs from the TSD method by 9 to 15 dB. In general the AFFDL method under predicts the aural detectability of the signals without tonal content.

4. The TSD prediction method specified in Section IV of this report works equally well for aircraft noise signatures containing broadband noises and pure tones, without requiring distinctions to be made between them.

5. The efficiency of a human observer with respect to an ideal energy detector in a quasi-realistic detection situation is 0.4.

6. For a fixed false alarm rate of about 1%, 1.2 dB separate the 25% and 50% correct response points on the psychometric function describing aircraft detectability, while 0.9 dB separate the 50% and 75% correct response points.

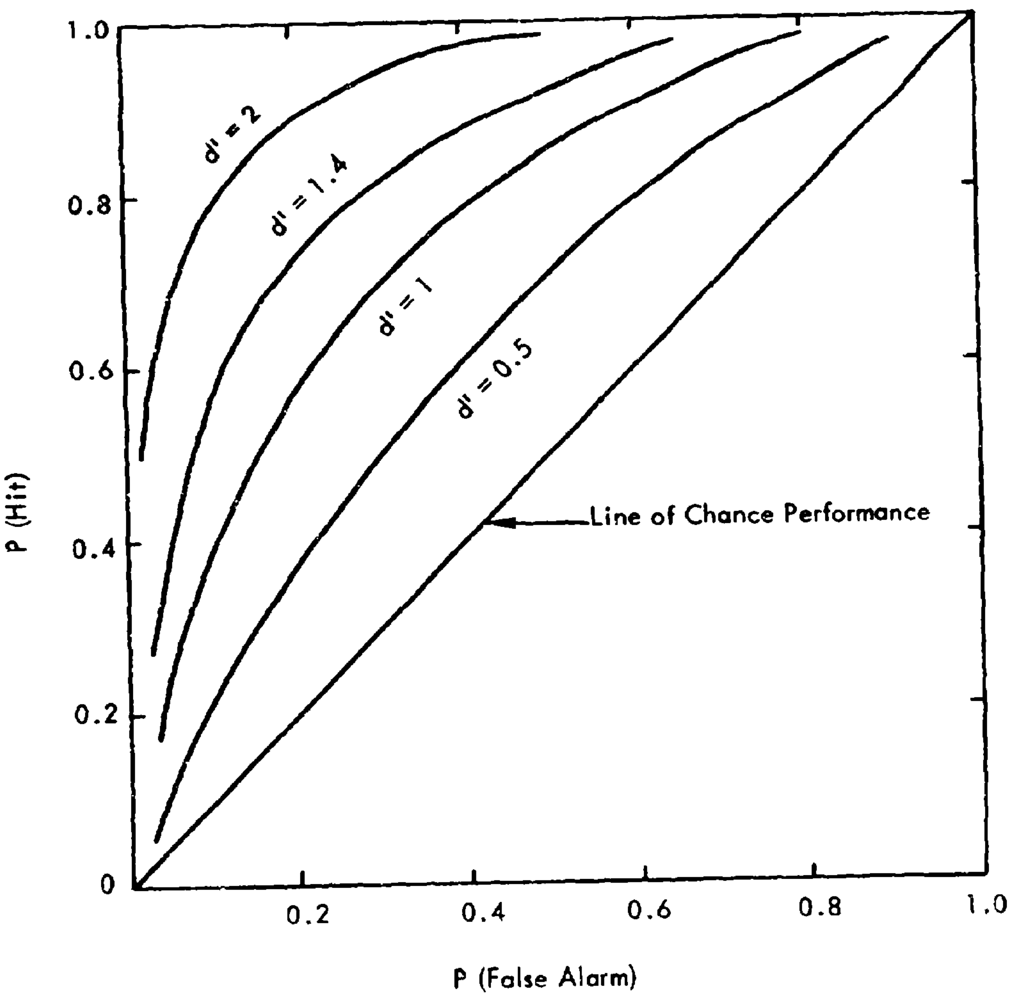


FIGURE 1. A FAMILY OF RECEIVER OPERATING CHARACTERISTIC CURVES

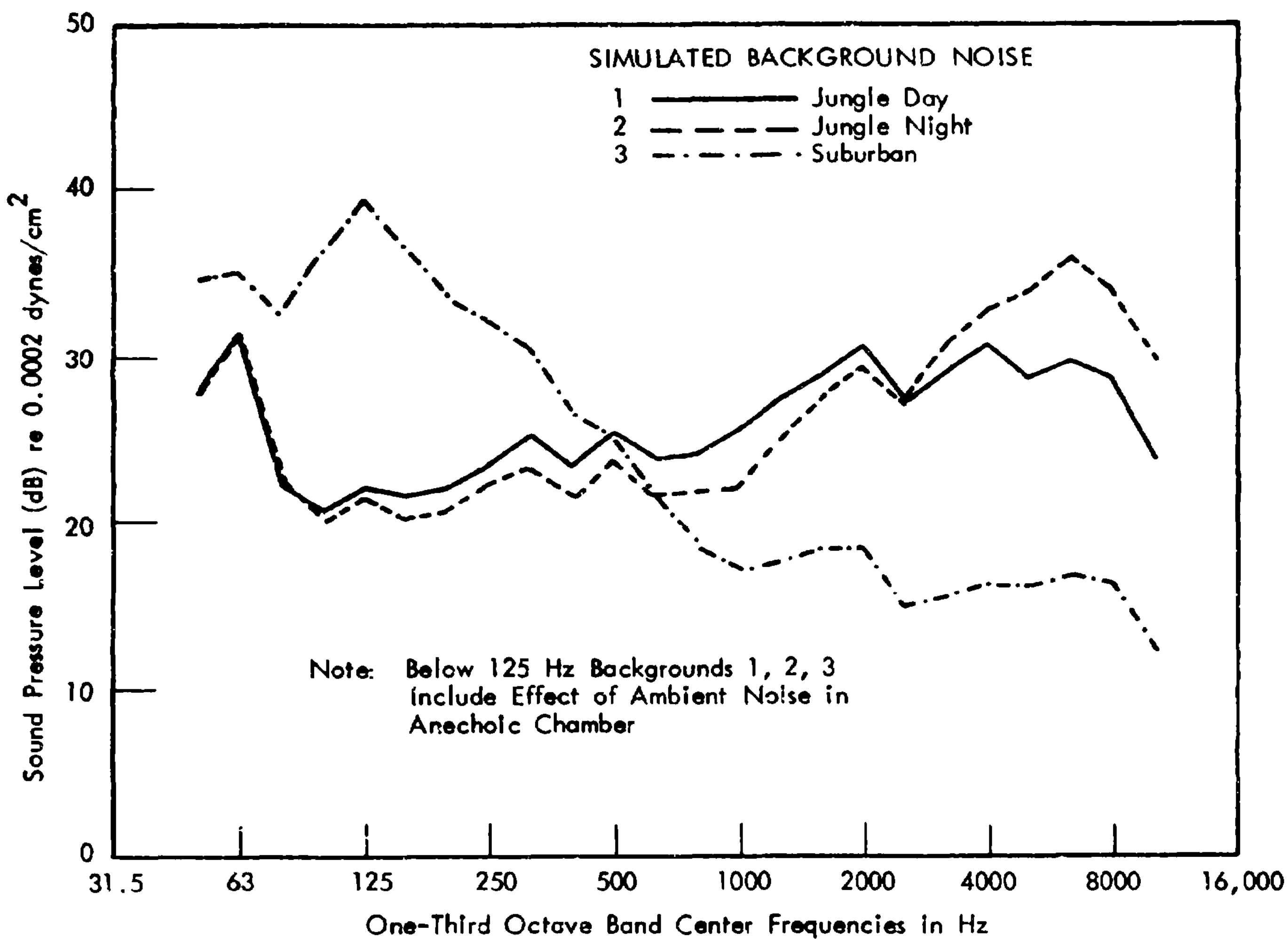


FIGURE 2. BACKGROUND NOISES FOR TEST IA AND IB

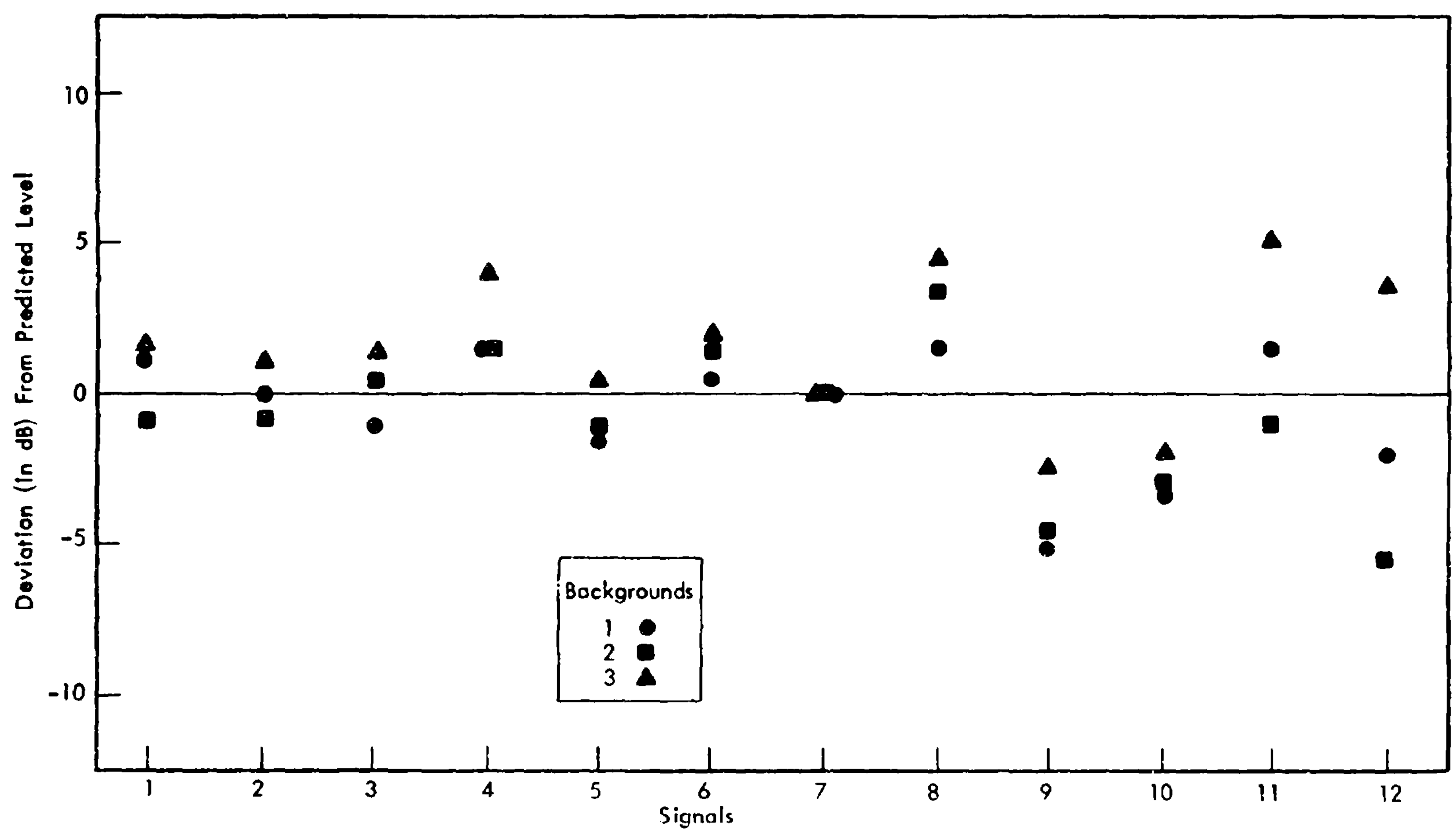


FIGURE 3. RESULTS FOR TEST IA FOR BACKGROUNDS 1, 2, 3

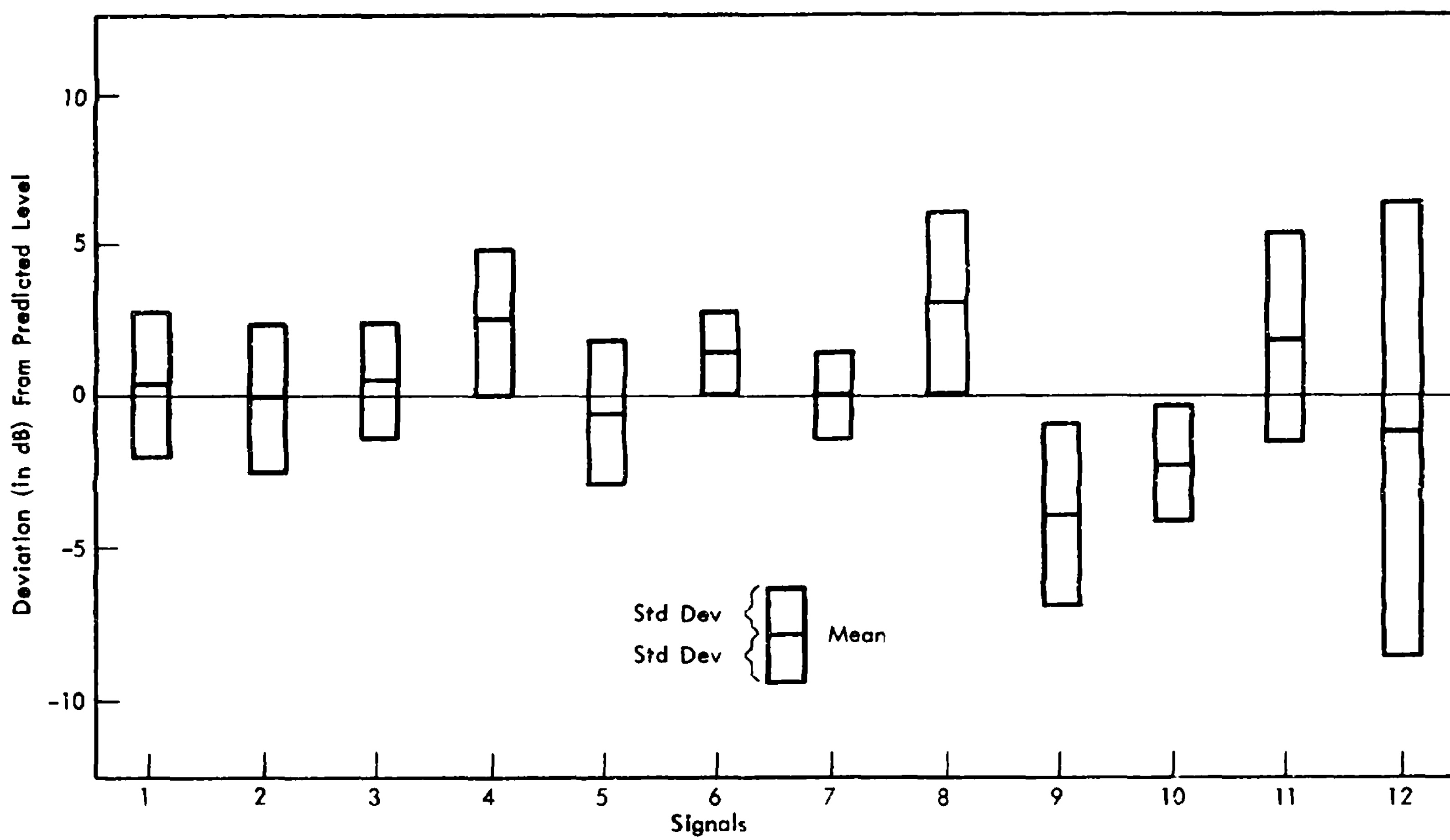
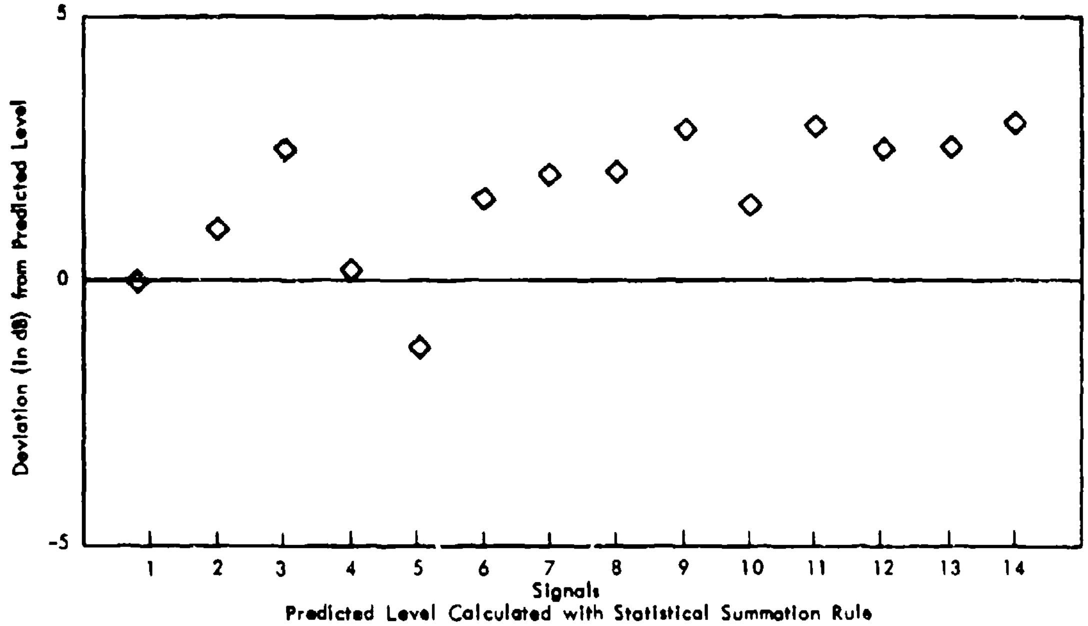


FIGURE 4. RESULTS FOR TEST IA - MEAN AND STANDARD DEVIATION OF SIGNALS FOR ALL BACKGROUNDS



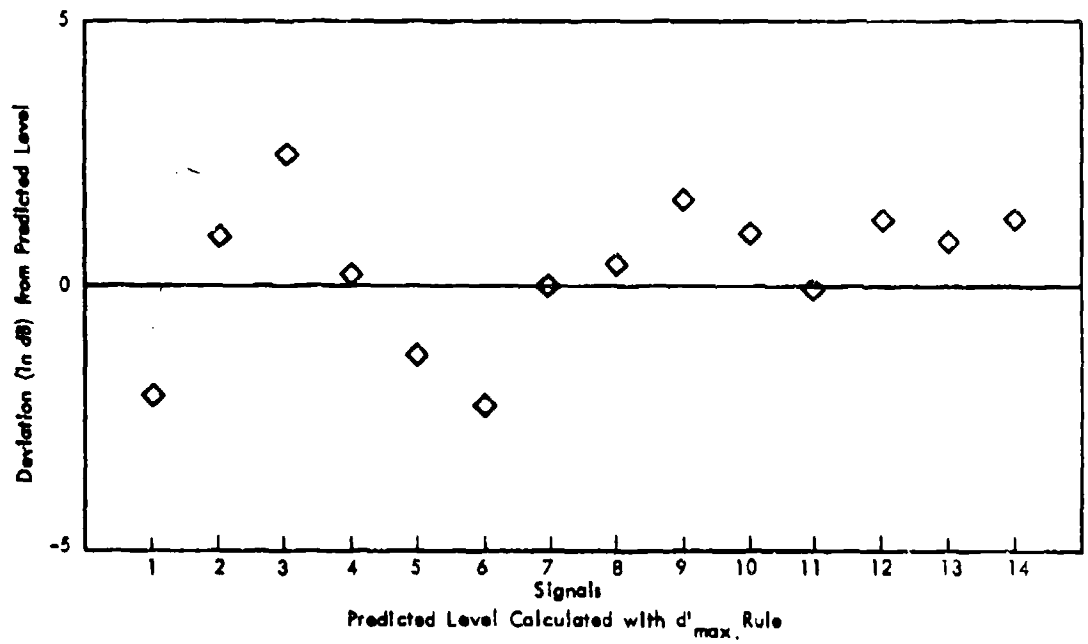


FIGURE 5. TEST IB - WITH BACKGROUND 1 - COMPARISON OF STATISTICAL SUMMATION PROCEDURE AND $d'_{max.}$ RULE

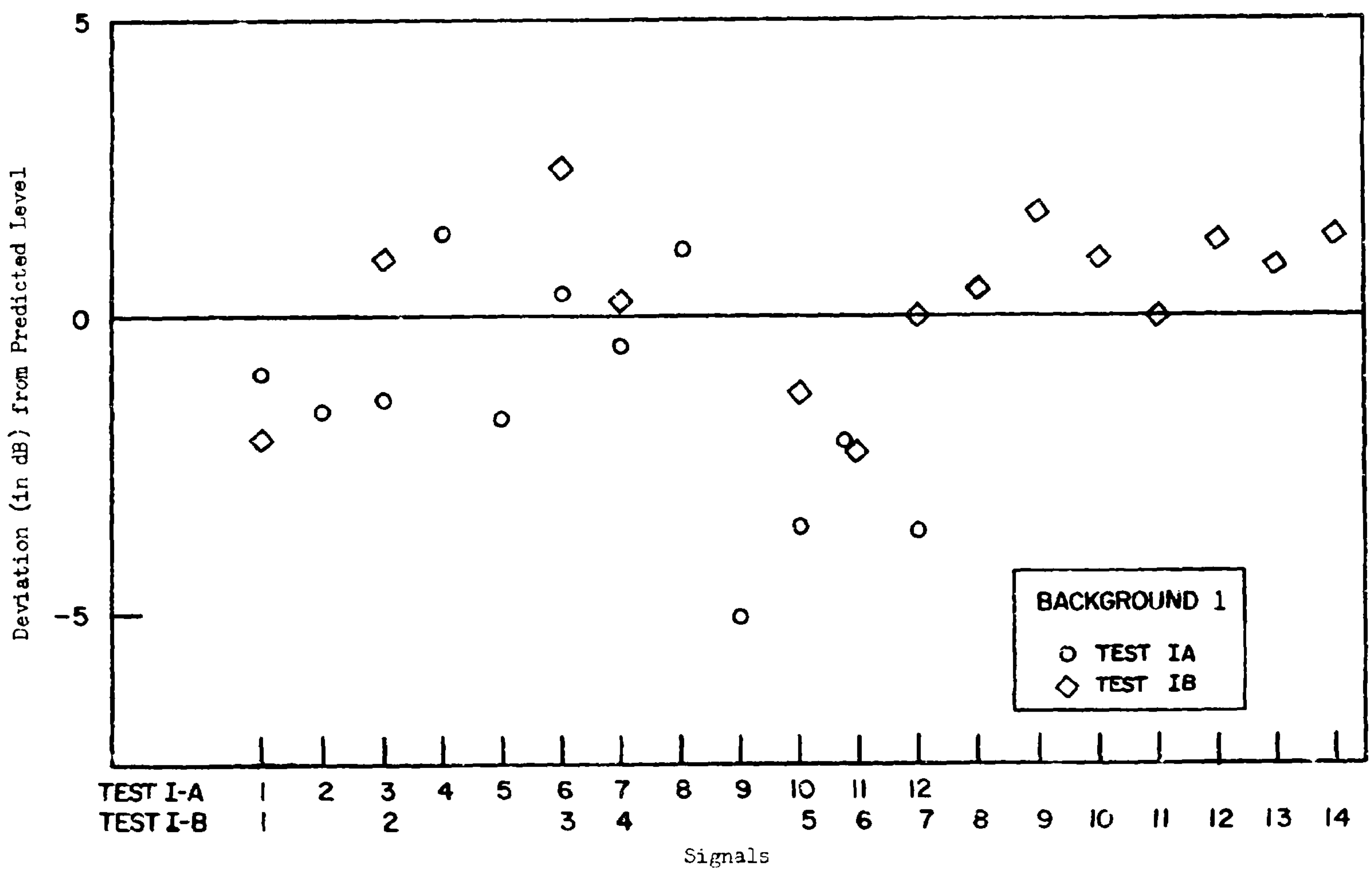


FIGURE 6. PREDICTED LEVEL CALCULATED WITH d'_{max} RULE FOR BACKGROUND 1 - TEST I A AND TEST I B

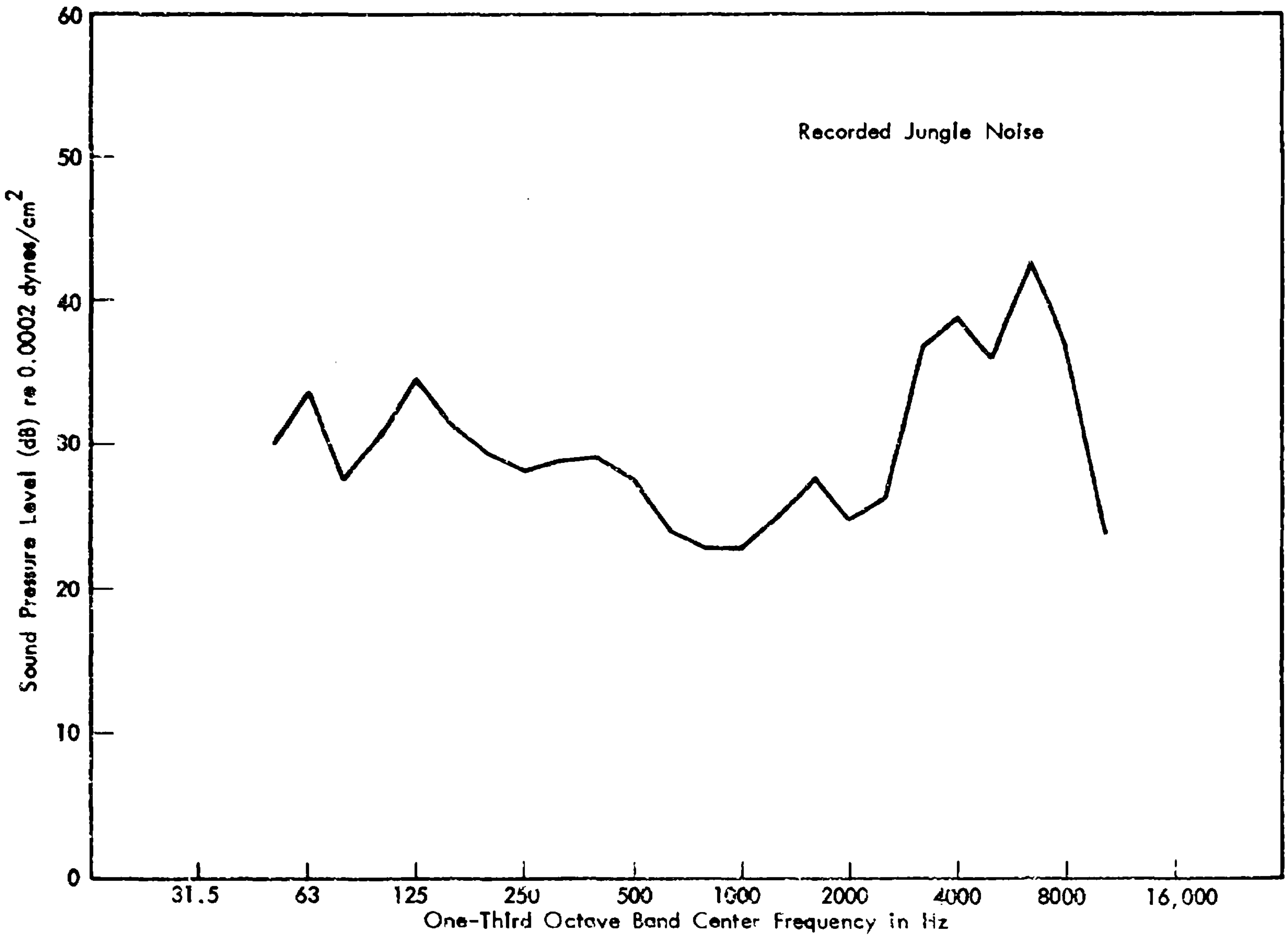


FIGURE 7. BACKGROUND NOISE FOR TEST II

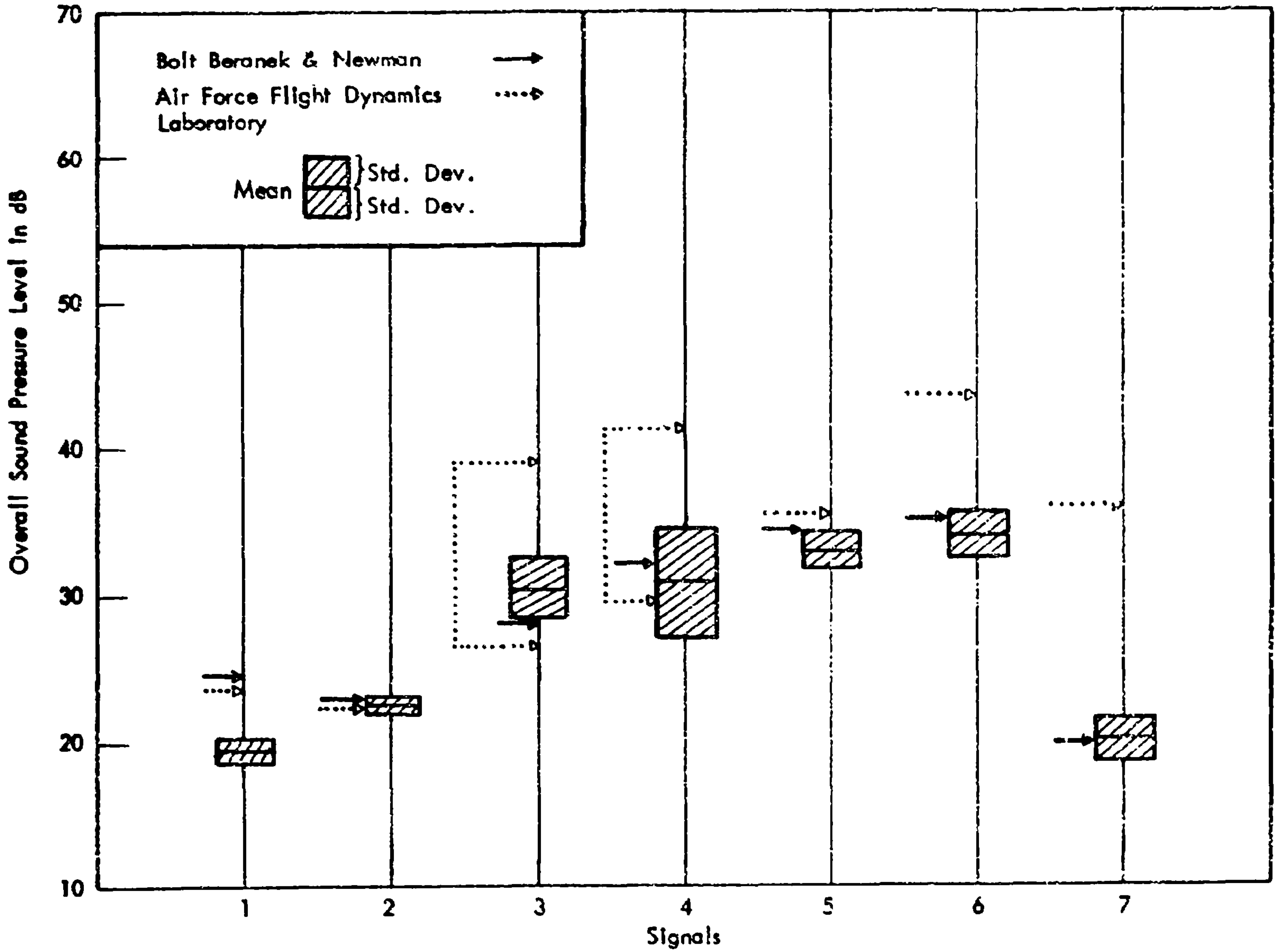


FIGURE 8. RESULTS FOR TEST II WITH JUNGLE NOISE BACKGROUND

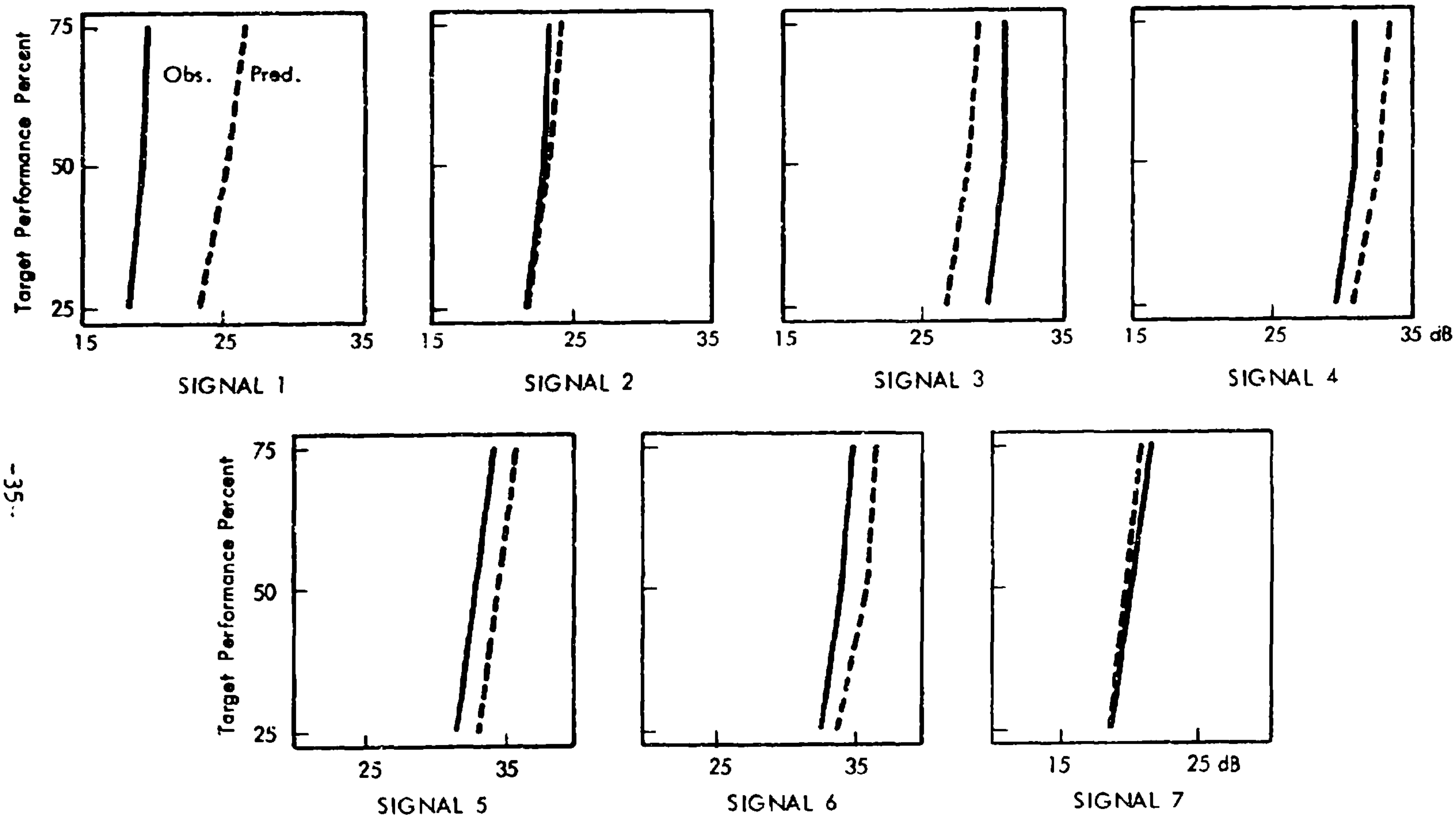


FIGURE 9. PREDICTED AND OBSERVED SIGNAL LEVELS FOR VARIOUS CORRECT DETECTION RATES IN TEST II (ABSCISSA IN OVERALL SPL)

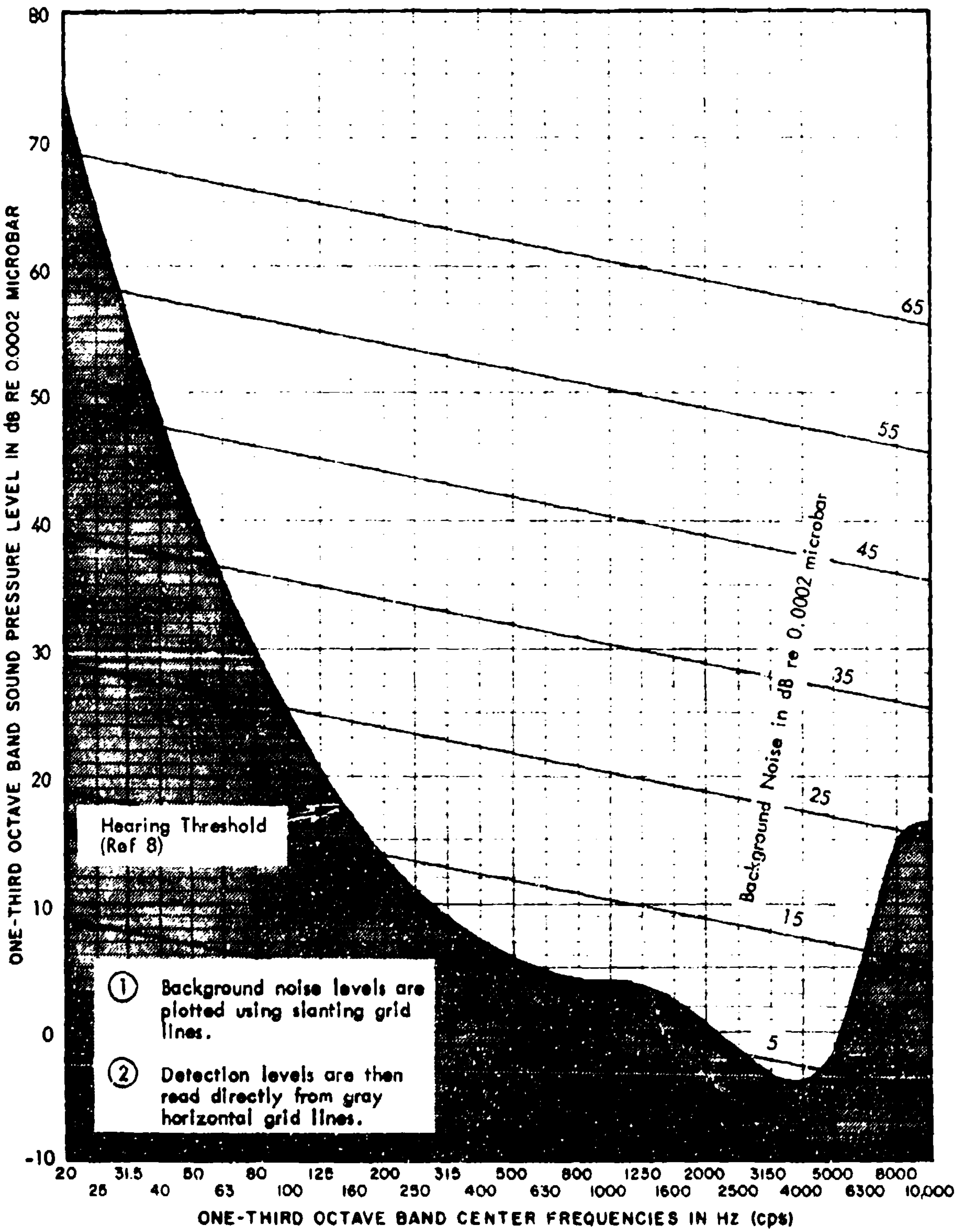


FIGURE 10. CHART FOR PREDICTING DETECTION LEVELS (FOR 50% CORRECT AND 1% FALSE ALARM RATES) USING BACKGROUND NOISE SPECTRUM IN ONE-THIRD OCTAVE BANDS

APPENDIX I.

SPECTRA OF TEST SIGNALS

TABLE I

SIGNALS FOR TEST IA

No.	Signal Type	OASPL	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
		Sound Pressure Level in dB re 0.0002 dyn/sq. cm. One-Third Octave Band Center Frequency, Hz.																								
1	T FM	68.1													32.6	57.5	62.7	63.7	62.5	36.1	25.6	26.1				
2	T FM	68.6													32.1	57.5	63.2	64.0	63.3	37.9	26.6	27.5	24.9			
3	N AM	64.6									29.3	49.8	63.9	55.4	29.2											
4	N AM	65.0															31.6	53.9	64.3	54.7	29.5	29.0				
5	N AM	65.2									30.2	51.2	64.4	56.4	[illegible]											
6	N AM	65.7															32.6	54.8	64.0	55.4	29.9	28.7				
7	N	66.4									30.7	51.8	65.6	57.0	30.7											
8	N	66.5															33.9	55.8	65.7	55.8	30.5	29.8				
9	T	61.2							40.8	61.2	39.3															
10	T	59.9																37.6	59.8	40.7						
11	N BB	64.9	31.7	30.9	38.5	51.5	56.5	52.7	50.9	55.8	56.6	53.0	51.2	50.7	51.6	51.6	52.9	50.7	50.3	46.8	45.6	46.5	47.4	46.4	45.5	38.3
12	N BB	63.6	44.1	42.7	44.3	56.0	59.4	55.3	52.4	52.0	52.6	45.4	44.1	41.2	38.6	38.6	38.8	38.1	37.3	33.0	33.4	34.1	34.7	35.3	35.3	30.9
BKG 1	N BB	40.3	28.3	31.0	22.1	20.3	21.1	21.5	21.9	23.2	25.1	23.4	25.4	23.8	21.9	25.5	27.4	28.8	32.3	27.6	29.5	30.5	29.9	29.6	28.6	23.6
2	N BB	42.1	28.1	30.8	22.4	19.8	21.3	20.0	20.7	22.0	23.1	21.4	23.3	21.2	20.9	22.0	24.9	27.3	31.0	27.7	30.7	32.7	33.8	35.8	33.9	29.7
3	N BB	44.6	34.3	35.1	32.6	36.6	39.5	36.6	33.6	32.3	30.6	26.5	24.8	21.4	18.1	17.1	17.3	19.1	20.2	14.7	15.3	16.0	15.9	16.4	14.1	12.3

1. T FM = Tone Frequency Modulation
   N AM = Noise Amplitude Modulation
   N = Noise
   T = Tone
   N BB = Noise Broadband

2. Unless otherwise noted the bandwidths of the signals are in one-third octave bands.

3. Possible maximum presentation levels

TABLE II
SIGNALS FOR TEST IB

Signal No.	Signal Type	OASPL	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
		Sound Pressure Level in dB re 0.0002 dyn/sq. cm. One-Third Octave Band Center Frequency, Hz.																								
1	T FM	65.4													27.6	53.8	60.2	60.6	60.2	34.9						
2	N AM	63.9									29.0	43.5	63.1	54.9	28.3											
3	N AM	63.9															31.2	52.8	63.1	53.7	27.9					
4	N	65.3									29.7	50.9	64.6	56.3	29.6											
5	N BB	58.6																36.5	58.6	39.1						
6	N BB	53.5	34.1	31.6	37.0	48.8	54.9	49.5	49.0	53.9	55.3	51.2	50.5	49.6	50.6	50.2	52.0	50.0	44.3	45.9	44.8	45.6	46.9	45.8	45.2	38.7
7	N BB	61.5	43.6	42.0	41.0	53.2	56.9	53.0	51.6	51.6	51.0	43.2	42.4	39.1	36.6	35.7	36.0	35.4	33.8	29.0	28.5	28.4	26.5	28.1	27.4	22.6
8	COMB.	65.8	41.8	39.7	40.1	53.1	56.9	52.5	49.5	47.7	40.1	37.0	50.9	51.7	35.6	34.5	35.0	48.2	61.2	50.5	29.1	28.3				
9	COMB.	66.1										45.0	58.4	49.9	27.3	51.2	57.6	58.2	62.5	50.7	29.7					
10	COMB.	65.0			29.1	41.5	47.9	42.8	40.6	45.0	46.9	43.1	62.0	51.7	41.8	41.4	42.6	49.1	59.1	50.5	38.2	34.3	35.2	34.0	32.5	
11	FO	70.3	40.5	47.9	49.9	57.1	60.9	56.3	55.2	56.2	57.9	[illegible]	62.8	57.4	54.8	60.8	56.4	55.8	56.3	53.1	53.3	55.3	60.9	49.6	48.1	40.8
12	FO	71.8	39.2	44.9	45.8	56.3	66.9	56.3	59.0	62.3	63.1	52.5	59.2	55.0	59.2	56.0	56.1	54.7	52.3	48.2	47.0	51.7	52.6	46.7	52.1	44.1
13	FO	71.9		44.0	51.1	61.6	67.7	64.9	60.9	64.2	57.9	[illegible]	58.7	49.1	46.5	43.3	4[illegible].0	41.4	38.4							
14	FO	68.8	41.7	33.9	57.6	61.6	62.0	60.0	56.9	60.1	5[illegible]	[illegible].3	55.3	52.1	47.8	46.1	47.0	45.6	43.6	40.3	40.9	42.4	41.7	42.6	41.4	35.1
BKG 1	N BB	41.3	27.6	31.7	22.7	21.0	24.2	23.0	22.7	24.9	26.[illegible]	[illegible]	26.[illegible]	25.4	25.4	26.6	[illegible].3	30.2	41.0	[illegible].1	30.4	31.2	31.1	30.9	30.3	26.9

1. T FM = Tone Frequency Modulation
   N AM = Noise Amplitude Modulation
   N = Noise
   N BB = Noise Broadband
   COMB. = Combination
   FO = Flyover

2. Unless otherwise noted the bandwidths of the signals are in one-third octave bands

3. Possible maximum presentation levels

TABLE III
SIGNALS FOR TEST II

Signal No.	Signal Type	Sound Pressure Level in dB re 0.0002 dyn/sq. cm. One-Third Octave Band Center Frequency, Hz. OASPL	50	63	80	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
1	T FM	65.9														54.5	60.9	61.5	59.9	34.6						
2	COMB.	65.7										44.9	58.3	50.0	27.3	51.5	57.5	58.1	61.6	49.6						
3	FO	70.1	40.5	46.0	59.4	57.1	60.4	56.0	55.3	56.1	58.7	56.6	61.2	57.6	55.3	60.4	56.3	56.0	55.7	53.1	52.7	55.1	60.6	49.1	49.1	41.7
4	FO	71.5	37.3	42.3	44.8	55.8	66.2	55.7	58.1	61.7	63.0	58.3	58.7	57.4	57.8	56.3	55.9	54.5	52.4	48.3	47.2	53.2	54.4	49.8	56.3	49.5
5	FO	71.5	34.0	42.0	50.0	61.2	67.1	64.5	60.6	63.8	58.0	53.0	54.2	48.9	46.7	42.8	42.1	41.2	38.1	36.1	35.7	35.1	33.8	34.3	35.9	
6	FO	68.3	40.9	31.8	56.9	61.0	61.2	59.4	56.3	59.7	55.7	54.4	55.0	51.8	47.5	45.5	46.4	45.4	42.6	39.7	39.8	41.8	41.2	42.7	42.1	35.7
7	N AM	62.2															29.8	51.7	61.3	52.4						
BKG	Jungle	47.2	29.8	33.5	27.6	30.7	34.4	31.3	29.1	28.2	28.7	28.9	27.9	23.6	22.4	22.5	24.8	27.9	24.7	26.2	36.9	38.5	35.9	42.1	37.2	23.4

1. T FM = Tone Frequency Modulation
   COMB. = Combination
   FO = Flyover
   N AM = Noise Amplitude Modulation

2. Unless otherwise noted the bandwidths of the signals are in one-third octave bands

3. Possible maximum presentation levels

APPENDIX II.
INSTRUCTIONS TO OBSERVERS

1. Observer's Instructions for Test IA and IB

You are about to participate in an experiment which will test your ability to hear a number of faint sounds. The sounds will occur in distinct trials. Each trial is composed of two listening intervals. The buttons in front of you labelled 1 and 2 light up during the first and second listening intervals of each trial, respectively. After listening during the two intervals, your job is to push either button 1 or button 2, corresponding to the listening interval in which you think the sound has occurred.

The sound you are listening for will occur equally often in each listening interval, but in random sequence. Since there is no pattern whatsoever to the order in which the sound appears in the two listening intervals, you must base your decision solely upon what you hear.

You will hear a sample of the sound for which you are to listen before each experimental session begins. After the experimental session has begun, a constant background of noise will always accompany the sound for which you are to listen. On some trials the level of the sound you are listening for will be so low that you will have difficulty deciding which listening interval contained the sound. Regardless of how confident you feel about your decision, you must push one of the two buttons on each trial. Remember that the sound you are listening for always occurs on each trial, even if you are not certain of the interval in which it occurs.

Directly after your response on each trial the button corresponding to the listening interval in which the sound actually did occur will light up briefly. You will therefore know immediately whether your decision was correct or incorrect. Since the next trial cannot be presented until you have made your decision about the preceding trial, you should decide as quickly as is convenient which interval contained the sound.

An experimental session continues until your percentage of correct decisions has reached a predetermined level. In order to end an experimental session as rapidly as possible, it is therefore necessary for you to listen very carefully on each trial, and to make your decision as best you can.

When you are ready to start an experimental session, push the button labelled "PAUSE". If at any time during the experiment you must pause momentarily (as, for example, to ask the experimenter a question) push the pause button. The PAUSE button will also light at the end of each session. When it goes out again you may push it to start the next experimental session. In responding you must wait until the end of the second listening interval (i.e., until the light in button 2 has been extinguished) before you push either of the buttons.

2. Observer's Instructions for Test II

You are about to participate in an experiment that will test your ability to hear certain faint sounds. Before the start of an experimental session you will have an opportunity to hear the sound for which you will be listening. After an experimental session has started, a background noise will be heard continuously. Further, the sound you are listening for will not be of identical

loudness each time you hear it. Thus, at certain times you will be quite sure that you heard the sound, but at other times you will have considerable difficulty in deciding whether you heard it.

The sounds will occur at unpredictable times. Thus, you must listen carefully throughout the experimental session, which will last approximately one-half hour. Your task is to push the response button in front of you whenever you think you hear the sound for which you are listening. If you push the button while the sound is playing, or within a half second after the sound ceases, your response button will light up immediately after your decision.

If you push the button when the sound is *not* in fact being played, you will be fined a nickel to be subtracted from a $1.00 bonus for each session, payable immediately upon completion of the session. An experimental session will continue until your percentage of *correct* decisions has reached a predetermined level. In order for you to end an experimental session as rapidly as possible, it will be necessary to listen very carefully throughout the entire session and to make your decisions as best you can.

APPENDIX III.
OBSERVERS AND EQUIPMENT

1. Observers

The observers for the detection tests were male and female students ranging in age from 16 to 24 years with a median age of 20 years. Prior to testing the observers were audiometrically screened for hearing acuity within 15 dB of the ISO specified normal hearing threshold. The observers participated in the tests in two hour sessions with appropriate rest periods to prevent fatigue. Ten observers were employed in each of Tests IA and IB and nine observers were employed in Test II. Fewer observers were employed in Test II because of the reduced variance associated with the type of detection task.

2. Equipment

A complete list of all equipment employed in signal presentation and analysis is provided in Table I. The equipment employed in the presentation of the test signals to observers is further illustrated in a block diagram in Figure 11. As indicated in the figure, a digital computer controlled the presentation of the test signals to observers. The levels of the signals were also controlled by the computer using information supplied by the subject's responses in accordance with the adaptive procedure known as Parameter Estimation by Sequential Testing (PEST) (Reference 3). The majority of signals were recorded on four second long tape loops and stored in cartridges for use in the six channel cartridge tape recorder. The background noise was played on one of the channels and the signals selected by the computer were played back on one of the remaining five channels. The pure tones (250 Hz and 2000 Hz) were generated directly by an oscillator. The level of the signals was amplified or attenuated by the voltage

controlled amplifier or a digital attenuator, both of which were under computer control. The voltage controlled amplifier had the capability of continuous control of the level over a 60 dB range. For purposes of the judgment tests the smallest steps were 1 dB. The digital attenuator further controlled the signal in 10 dB steps to allow an extension of the dynamic range of the system. The electronic switch incorporated a rise-decay time of 100 milliseconds to eliminate any transients or clicks which might provide special clues for the subjects in the detection process.

In addition to the level control by the computer, manual attenuators were added to maintain proper balance and additional control for the various signals and background noises employed in the detection tests. The signal and background were played through a mixer followed by a power amplifier to the loudspeaker in an anechoic chamber where the tests were administered. To insure proper calibration in the system, voltage levels were continually monitored across the loudspeaker throughout the duration of the test. The acoustic levels measured in the anechoic chamber were related to the voltage across the loudspeaker in an initial set of acoustical measurements. The acoustical measurements were made in one-third octave bands using a 1 inch condenser microphone, a cathode follower, and a sound level meter which in turn was connected to a tape recorder. The microphone was placed at the location of the observer's ear, without the observer present. This location was on axis two meters in front of the loudspeaker in the anechoic chamber. The tape was later played back through a one-third octave band real time analyzer to determine each maximum one-third octave band level of the signal. Measurements of the signal were performed with the system gains at maximum while the background noise measurements were made using the actual levels employed in the detection tests. For the recordings of jungle background noise which exhibited greater level variation than the

shaped broadband noises of Test IA and IB an average level was employed. The level was determined statistically by sampling every 0.5 second and noting the level in each one-third octave band which was exceeded 50% of the time. Maximal signal levels were read into the computer so that the computer was able to print out the final detection levels by simply keeping track of the amount of gain and attenuation employed in the signal presentation.

TABLE I.

EQUIPMENT EMPLOYED FOR SIGNAL PRESENTATION AND ANALYSIS

Item	Make	Model	Pertinent Characteristics
Presentation Equipment			
Computer	Digital Equipment Corp.	PDP-8	12 Bit D/A Converter, Interrupt System, Interfacing, and Appropriate Software
Oscillator	Krohn-hite Corp.	4024-R	Frequency Range 0.01 99.9 K Hz.
Tape Cartridge Recorder	KRS Instrument Corp. (Visual Electronics Corp.)	SB6AR1	6 Deck Tape Recorder Reproducer
Voltage Controlled Amplifier	Ithaco	311AM101	60 dB Range
Electronic Switches	Grason Stadler	829E	Rise Time = 100 ms
Digital Attenuator	Constructed by BBN	-	70 dB Range
Attenuator	Daven	T-693-R	110 dB Range in 0.1 dB Steps
Mixer	Constructed by BBN	-	Active Mixer with 0 dB Loss
Power Amplifier	James B. Lansing Co.	SE400S	40 Watts
Loudspeaker	James B. Lansing Co.	C-50	40-15,000 Hz ± 3 dB

TABLE I. (CONTINUED)

Item	Make	Model	Pertinent Characteristics
Measuring and Analysis Equipment			
Microphone	Bruel & Kjaer	4145	Diameter = 1" 10-18 K Hz ± 2 dB
Cathode Follower/ Power Supply	Bruel & Kjaer	2801	Response Limited by Microphone (4145)
Sound Level Meter	Bruel & Kjaer	2203	Response Limited by Microphone (4145)
Tape Recorder	Kudelski	Nagra III B	40-14,000 Hz ± 1 dB
Real Time Analyzer	Hewlett Packard	8054A	Filter Bandwidth -- 1/3 octave 24 Bands (Range of Band Center Frequencies -- 50-10,000 Hz) Nominal Time Constant = 1 sec. (corresponds to IEC 179 Standard for Sound Level Meters. Slow Meter Ballistics)
Computer	Digital Equipment Corp.	PDP-8	12 Bit, High Speed Minicomputer with Appropriate Interfacing and Software to Reduce Spectral Data

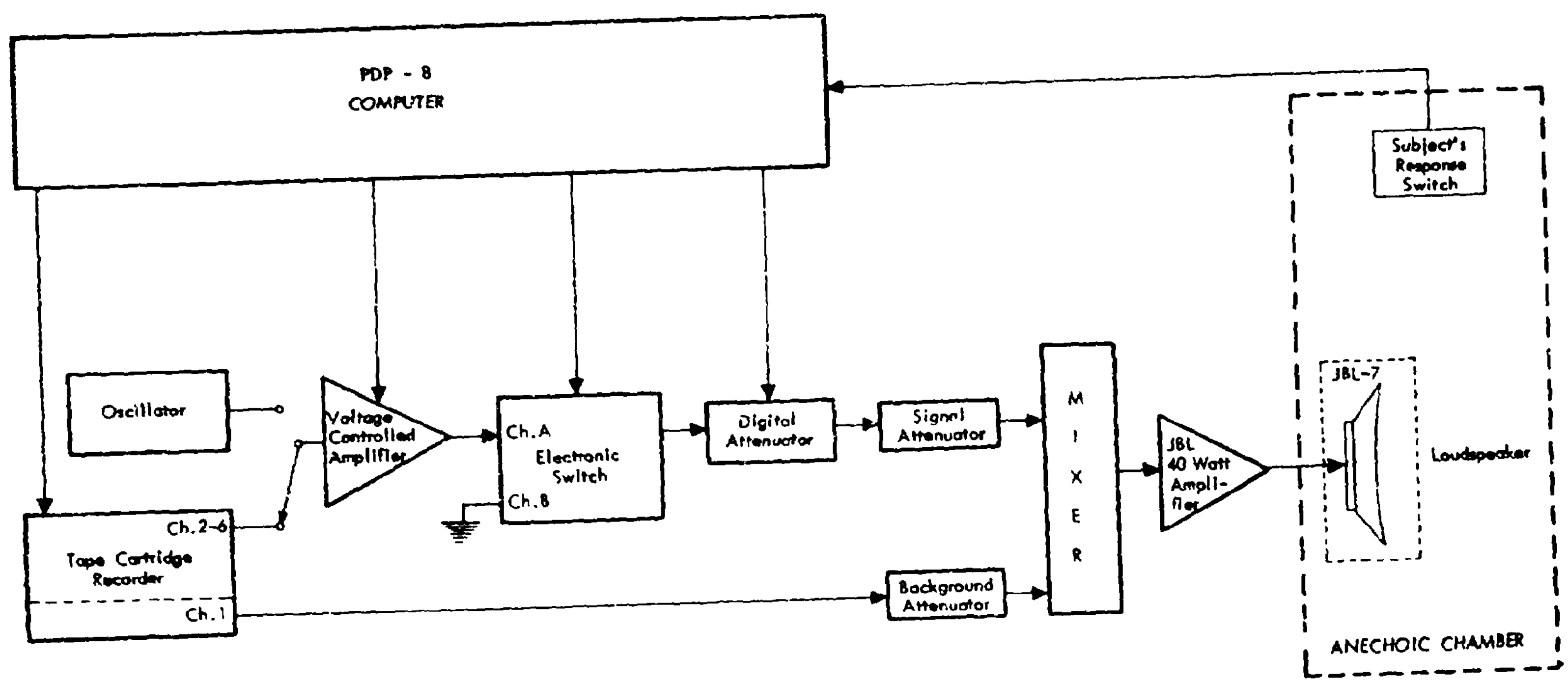


FIGURE 11. BLOCK DIAGRAM OF PLAYBACK SYSTEM FOR JUDGMENT TESTS

APPENDIX IV.

STATISTICAL SUMMATION METHOD

The purpose of this appendix is to describe the statistical summation procedure for predicting the detectability of a broadband signal in broadband noise. The appendix is included in this report primarily for the sake of completeness, since the statistical summation method was discarded in favor of the recommended procedure of Section II for reasons discussed in the text. Several simplifying assumptions are made in this analysis.

1. We assume both background and signal are independent, random processes, so that signal and background powers add simply.

2. We assume the background spectrum is reasonably flat. In particular, it is important that the power in successive octave bands does not fall more than 5 dB. This assumption is made to avoid difficulties inherent in considerations of the upward spread of masking.

3. We assume the duration of the signal exceeds one second.

Given these assumptions we use the approach outlined by Green (Reference 9) to determine the detectability of the noise signals. This approach is based on ideal detection considerations and assumes that the human auditory system can be likened to a simple energy detector. As Green (Reference 9) has shown, the bandwidth of the auditory system can apparently be matched to the spectrum of the signal.

Given a flat background and spectrum with noise density N_0 and a flat signal spectrum with density $\mathcal{E}_0$, the detectability of the signal depends only on the duration and bandwidth of the signal

and the ratio S_o/N_o. In fact, the detectability index d' is given by

$$d' = k(WT)^{\frac{1}{2}} \frac{S_o}{N_o}$$

for T > 1 sec

$$d' = 2/5\ W^{\frac{1}{2}} \frac{S_o}{N_o}$$

For this simple case, (flat signal and background spectra), the signal-to-noise ratio needed for the signal to be detected with any given probability as a function of a signal-to-noise ratio may be readily calculated. Thus, if the signal bandwidth is 5000 Hz, the signal level can be 14.5 dB below the noise level for the signal to be detectable 76% of the time in a 2AFC task.

For more complicated spectra the rules for predicting the detectability are more cumbersome but conceptually quite simple. Consider a series of octave or third octave measurements of the signal and background spectra. Let $(S/N)_i$ be the signal-to-noise ratio (power ratio) in the ith octave band. In the general case $(S/N)_i$ will change from one band to the next and the detectability will depend primarily on the most detectable band. In fact, it is established that the total detectability is simply

$$d' = \left| \sum_{i=1}^{n} d_i^{\,2} \right|^{\frac{1}{2}} = \left| \sum_{i=1}^{n} [2/5 W_i^{\frac{1}{2}}\ (S/N)_i]^2 \right|^{\frac{1}{2}}$$

That is, the detectability index for the different bands should be combined according to the rules of vector addition. Since each band is independent of all others, each d_i is treated as an orthogonal vector. Note that the total d' is proportional to the signal-to-noise ratio in each band. Thus, one may raise the detectability by a factor of 2 by increasing the signal level 3 dB.

APPENDIX V.

CONDENSED SUMMARY OF PROCEDURES FOR EVALUATING THE AURAL DETECTABILITY OF AIRCRAFT

1. Evaluation of Predicted Aircraft Noise Signature

a) Determine the maximum one-third octave band spectrum of the total aircraft noise signature received on the ground from a reference altitude (R_o) using state-of-the-art prediction methods (i.e., Reference 10).

b) Determine the one-third octave band spectrum of the most critical background noise environment in which the aircraft will operate. (Background noise measurements are available in the literature, i.e., Reference 6.)

c) Plot the one-third octave band spectrum of the total aircraft noise signature using the horizontal grid of Figure 12. Plot the one-third octave band spectrum of the background noise using the slanted grid of Figure 12 which determines the detection level.

d) For each one-third octave band, determine the difference (in dB) between the level of the aircraft noise signature and the detection level. This difference represents the amount of noise reduction required in each one-third octave band to render the signal detectable 50% of the time in the given background noise. Alternatively, if it is not possible to reduce the aircraft noise by this difference, the aircraft must be flown at a greater altitude. In Reference 2 an expression is presented for determining the excess altitude to obtain the required noise reduction. The expression is as follows:

$$\Delta SPL = 20 \log \frac{R}{R_o} + K (R-R_o) \qquad (1)$$

where, ΔSPL = the difference between the measured or predicted aircraft one-third octave band noise level and the detection level, (dB).

R_o = the reference altitude, (feet)

R = the altitude above which the noise received from the aircraft will be undetectable 50% of the time, (feet)

K = the atmospheric absorption coefficient for the frequency or center frequency corresponding to the level ΔSPL (see Reference 10), (dB/1000 feet).

This expression must be applied to each one-third octave band. The band which gives the greatest R represents the altitude at which the aircraft must be flown in order to reduce the received noise such that aircraft would be detectable 50% of the time with a 1% false alarm rate. As mentioned above, these detection rates can be adjusted to evaluate various probabilities of detection with a corresponding variation in the altitude required for a given detection rate.

2. Evaluation of Measured Aircraft Noise Signature

a) Obtain sufficient flyover noise measurement data of an aircraft to define a representative one-third octave band spectrum of the total aircraft noise signature.

b) Analyze the data from the flyover noise measurements in accordance with the procedures outlined in Appendix III in order to obtain a representative one-third octave band spectrum of the total aircraft noise signature.

c) Determine the one-third octave band spectrum of the background noise environment and evaluate the aural detectability of the aircraft as given in steps b, c, and d above.

3. Example

Figure 13 provides samples to illustrate the use of the graphic prediction method. The background noise plotted in Figure 13 is replotted using the special grid of Figure 12. The resulting levels are shown in Figure 14. The aircraft flyover noise of Figure 13 is now superimposed on the plot of Figure 14.

The superimposition indicates that the signal to noise ratio of greatest detectability is in the 315 Hz one-third octave band. It is further shown that the level of the signal must be reduced 26 dB to render the signal detectable 50% of the time in this jungle background. Alternatively, if it is not possible to reduce the aircraft noise to produce a 26 dB decrement in signal to noise ratio, the aircraft must be flown at an altitude greater than the altitude at which the current measurements were made to maintain detectability at the 50% correct rate. Using Equation 1 in step d, a reference altitude (R_o) of 125 feet and K = 0.5 dB/1000 feet, the altitude which the aircraft must fly to be detected 50% of the time is 2200 feet.

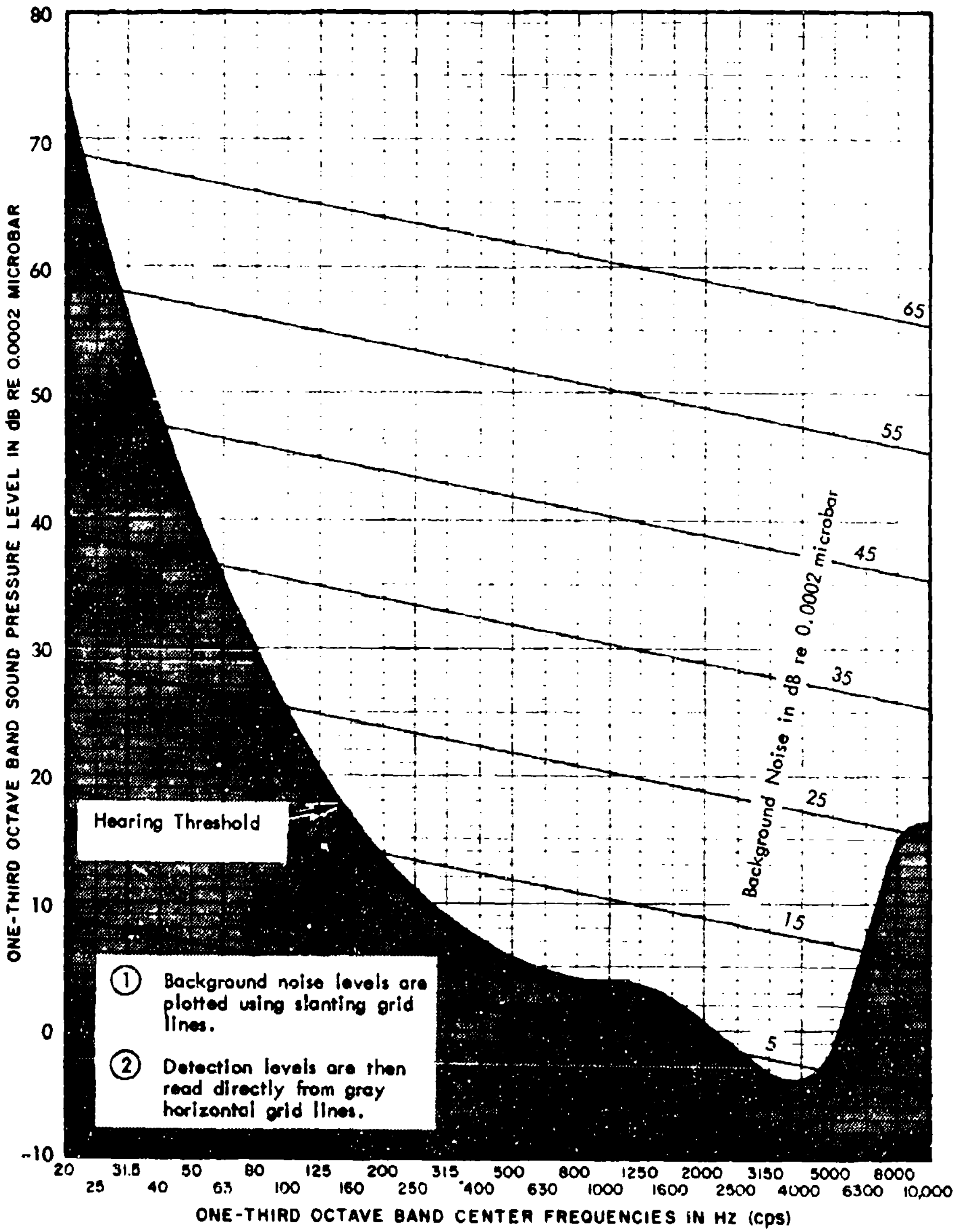


FIGURE 12. CHART FOR PREDICTING DETECTION LEVELS (FOR 50% CORRECT AND 1% FALSE ALARM RATES) USING BACKGROUND NOISE SPECTRUM IN ONE-THIRD OCTAVE BANDS

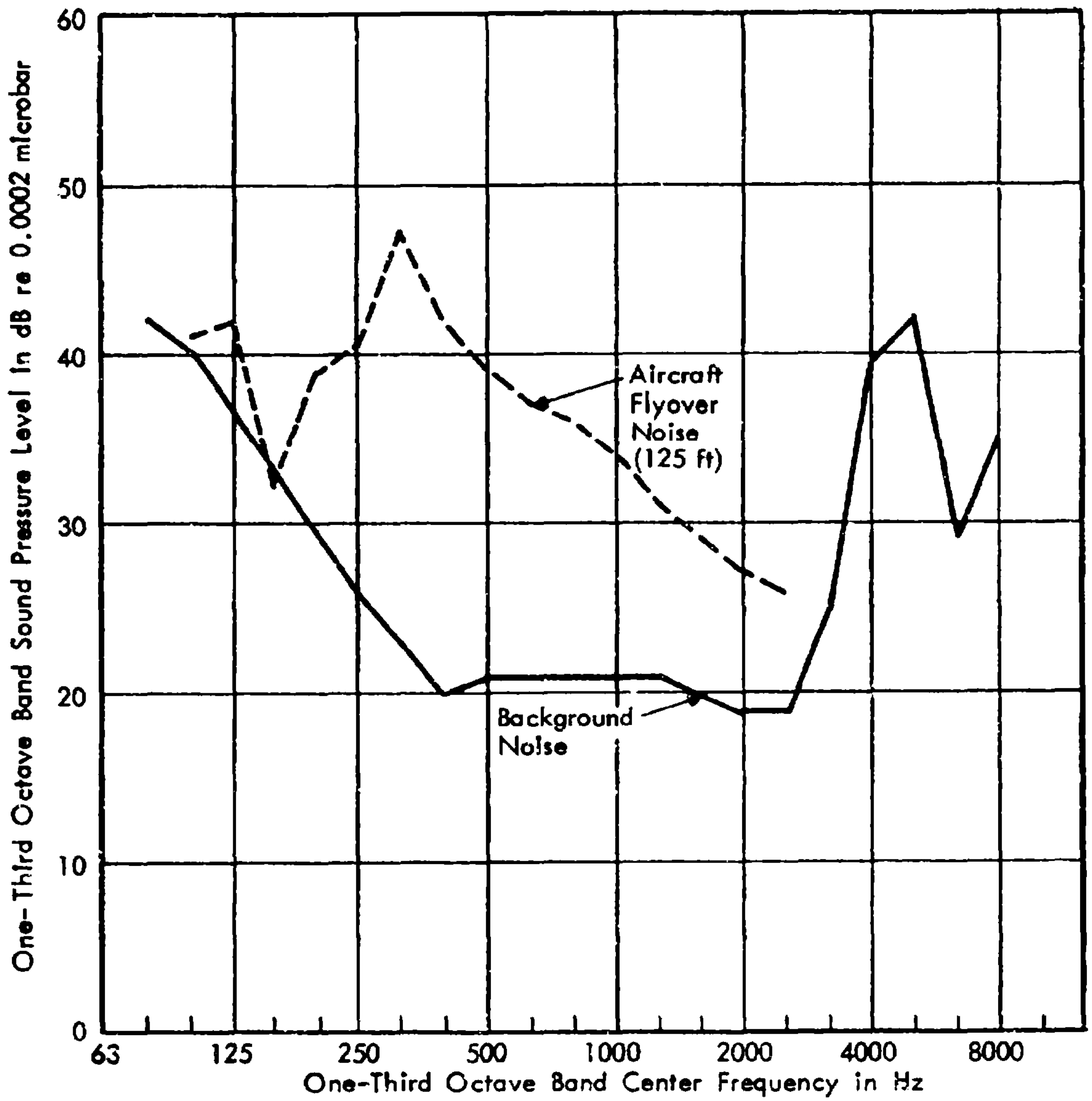


FIGURE 13. BACKGROUND NOISE AND AIRCRAFT FLYOVER NOISE SAMPLE

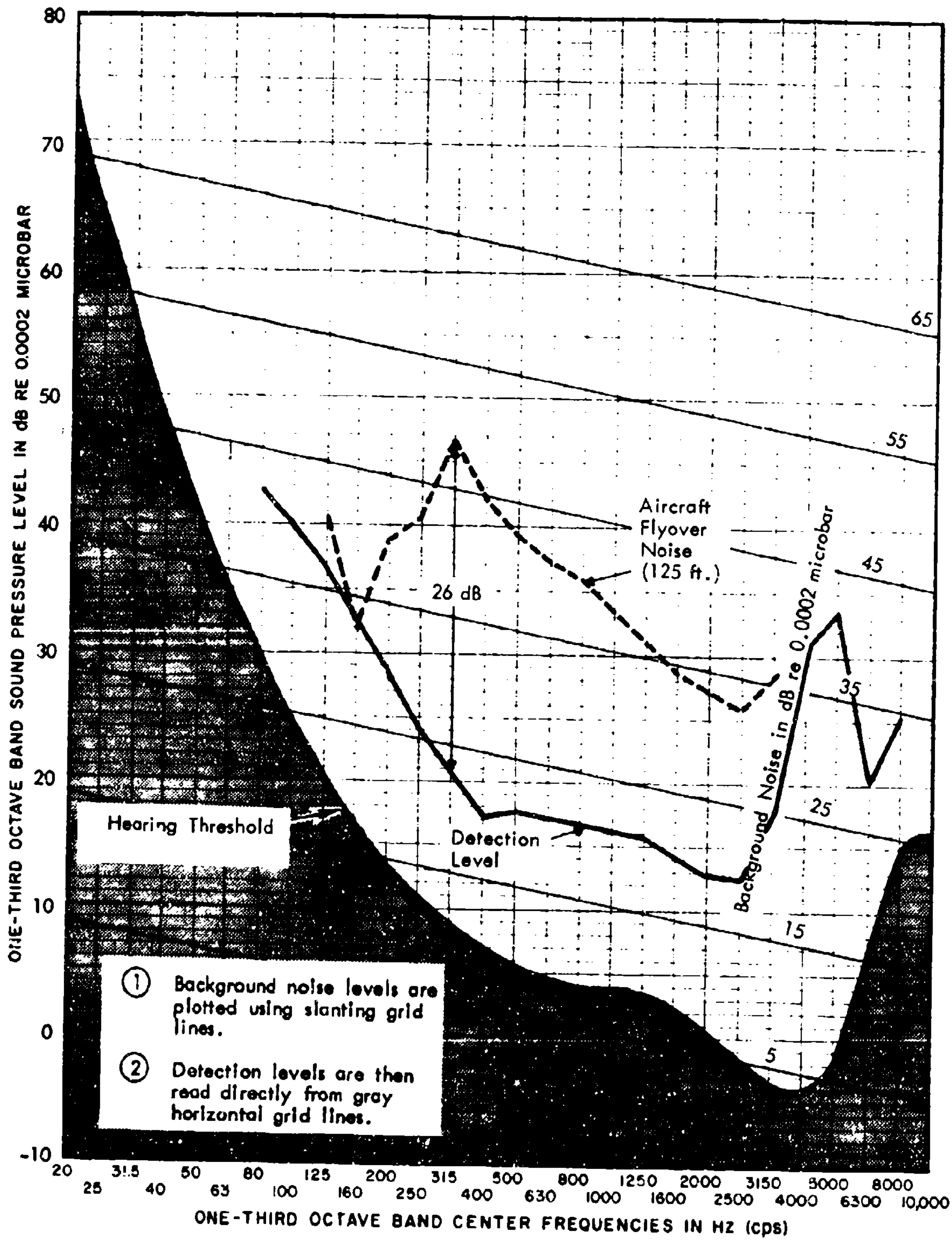


FIGURE 14. PREDICTED DETECTION LEVEL EXAMPLE FOR AIRCRAFT FLYOVER NOISE IN NOISE BACKGROUND

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13. ABSTRACT

Laboratory experiments were undertaken to develop improved aural detection criteria for light aircraft. Specifically two series of psychoacoustic judgment tests were conducted to determine the applicability of the psychophysical Theory of Signal Detectability (TSD) to prediction of the aural detectability of light aircraft noise signatures in jungle noise backgrounds. The first series of tests produced data supporting development of a simplified graphical prediction method based on TSD. The second testing program validated the precision and accuracy of the prediction method under quasi-realistic listening conditions. Predicted levels of performance were typically within one or two dB of the data averaged for all observers.

This report gathers together from a diffused literature of acoustics and psychology knowledge and data on methods of evaluating the aural detectability of sound radiated by military aircraft of the utility class. This report discloses methods used by the Air Force in evaluating such aircraft from the acoustical standpoint.

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